THE DEVELOPMENT OF

CLIMATIC DESIGN GUIDELINES

for

LOW-RISE LOW AND MIDDLE INCOME GROUP HOUSING

in

THE COMPOSITE HOT-DRY/MONSOON CLIMATES OF SOUTH INDIA.

by

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Synopsis

This thesis deals mainly with arriving at climatic design guidelines for enhancing thermal comfort within a built space. The author here wishes to state that greater emphasis is placed on the methods of analysis employed than on the climatic design guidelines themselves.

The building types considered are low-rise low and middle income housing situated in the hot dry monsoon climates of south India that employ traditional building materials and methods of construction.

Computerized thermal modelling using simulated weather conditions is the evaluation method used. The software employed for the purpose is DEROB (Dynamic Energy Response Of Buildings), for the thermal modelling part, and Degelman's WETHRGEN (Weather Generator), for the simulation of weather.

The studies are based on:

i) patterns of usage of housing units
ii) prevalent construction practices
iii) utilization of building materials
iv) evaluation of thermal performance

to arrive at climatic design guidelines that are readily understood, simple, practical and easy to implement.

Foreword

The quest for a set of workable climatic design guidelines for the hot dry monsoon climates of south India began a few years ago. In 1988 the author, then employed in a private architectural firm in Bangalore, India, was periodically involved in the designs for a public housing scheme in the nearby town of Mysore. The project contractors seemed to resist any form of innovative construction methods.[1] Their preferences seemed to suggest: "We are quite adept at doing what we have been doing all along and think it works quite well, thank you." This sort of resistance cropped up well after the contract documents were signed.

At the same time, however, there seemed to be no similar resistance from contractors who were employed, on a private basis, on projects involving the construction of individual houses and private developments. It seemed that architects in general had lesser control over public housing projects.

1. For instance, the architectural firm the author worked for had developed economical designs for floor slabs using a simple grid of locally available hollow clay blocks reinforced with steel, supported on precast RCC rafters and covered with a thin layer of concrete screed. This system was designed to eliminate shuttering cost and the expectation was that the combination of clay and air space within would provide better insulation. But the contractors, realising that a lot more care needed to be taken on site to see this implemented, simply went ahead and changed the specifications on site to a regular concrete roof because it did not suit their interests.

Public housing is a field of architectural design that potentially affects a vast number of people. The smallest of design flaws can quickly get magnified *due to the very repetitive nature involved in the designs.*

Therefore, considering the prevalent conditions in the local building industry with respect to public housing, which are:

a) The use of commonly available building materials (such as brick, stone and concrete)

b) The continued reliance on labour intensive construction methods (as labour is cheap)

and

c) The employment of simple construction methods involving load bearing walls and small span roof slabs (as labour employed is usually semi-skilled or unskilled and mensuration is often elementary[2])

it seemed appropriate to work with the existing fabric of construction materials and methods, and make subtle changes within them to achieve greater thermal efficiency and comfort in a built space.

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2. Measurements on site are mostly based on just a measuring tape supplemented by a ball of string (for straight lines), a plumb bob (for verticality), a plastic hose filled with water (for horizontality) and a tri-square (for right angles) - the author.

There seem to be any number of guidelines from local development organizations for managing areas built and their construction costs. Often local construction practice is taken for granted. Unfortunately, climatic design guidelines for specific local climates are hard to come by. Broad design guidelines for hot dry climates can always be obtained from architectural books dealing with climatic issues, but may be too general. The above aspects are investigated in this thesis.

Acknowledgements

The investigations in this thesis would not have come about without the astute guidance of the author's advisor Dr. Forrest Higgs, Director, Environmental Technology Laboratory, and lecturer, Department of Architecture, The Chinese University of Hong Kong. The author can find no words equal to the task of expressing his gratitude to him. His vast experience with climatic design investigations and far reaching insights at every level has made this thesis a valuable learning experience.

The author is also deeply indebted to Professor Tunney F. Lee, Chairman, Department of Architecture, The Chinese University of Hong Kong. It was Prof. Lee who, with his immense reservoir of patience, helped the author take his first tentative steps as an academic, providing those gentle nudges in the right direction, smiling through his early writings, offering a tip here, a suggestion there, a candid observation now and then, as only he inimitably can.

The author further wishes to thank all the other faculty members of the Department of Architecture who played various roles in the development of this dissertation, especially Dr. Ho Puay Peng, Ms. Leng Woo and Brian Sullivan, lecturers at the Department of Architecture, for initial guidance and help in identifying the key issues involved. Special thanks are also due to

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The author further thanks Dr. M. G. Chandrashekar, Scientific Secretary, Indian Space Research Organization, Bangalore, and all his good friends in Bangalore, for helping him obtain relevant weather data for the area under investigation.

In the end, thanks are simply not enough for Mr. V. K. Girdhar, architect, Bangalore, with whom the author had worked for many years before moving to Hong Kong. Most of the author's experiences with housing design came from working with Mr. Girdhar. His encouragement, support and sound judgement proved vital at the time the author contemplated going back to school.

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ABBREVIATIONS used:

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
CLO	A unit of thermal resistance of clothing
DEROB	Dynamic Energy Response Of Buildings
HIG	High Income Group
HUDCO	Housing and Urban Development Corporation
ISRO	Indian Space Research Organisation
KHB	Karnataka Housing Board
LIG	Low Income Group
MIG	Middle Income Group
MSDOS	Microsoft® Disk Operating System
MS-WINDOWS	Microsoft® Windows
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
UNIX	UNIX® operating system

Abbreviations specific to DEROB

DIG	Digitization of building geometry
GF	Geometric factors
WAL	Wall equations
LUM	Luminance tensors
SOL	Solar penetration
TL	Thermal loads
MATLIB	Materials Library

1.0 Background

One of the principal organizations behind public housing in India is the Housing and Urban Development Corporation (HUDCO). This body was established in 1970 as a Government of India undertaking. Its main objectives are to finance or undertake housing and urban development related construction programs. Agencies eligible for HUDCO's financial assistance include various state housing boards, city improvement trust boards and other such local development authorities.

In 1986 in the southern state of Karnataka (Fig. 1), HUDCO provided a great deal of financial assistance for housing for the Karnataka Housing Board (KHB) and the City Improvement Trust Board (CITB), Mysore, -- both of which are local development authorities. Realizing that their in-house capabilities were inadequate, the KHB and the CITB, Mysore, took a new initiative and decided to appoint many local practicing architects to design housing schemes in various towns all over the state (Sharma, 1987).

The major architectural design consideration put forth by HUDCO is strict cost control (Sharma, 1987), as these housing schemes are generally for middle and low income groups. HUDCO's funding is inversely proportional to income group, with the greatest subsidies for low-income housing, lesser subsidy for middle-income housing and

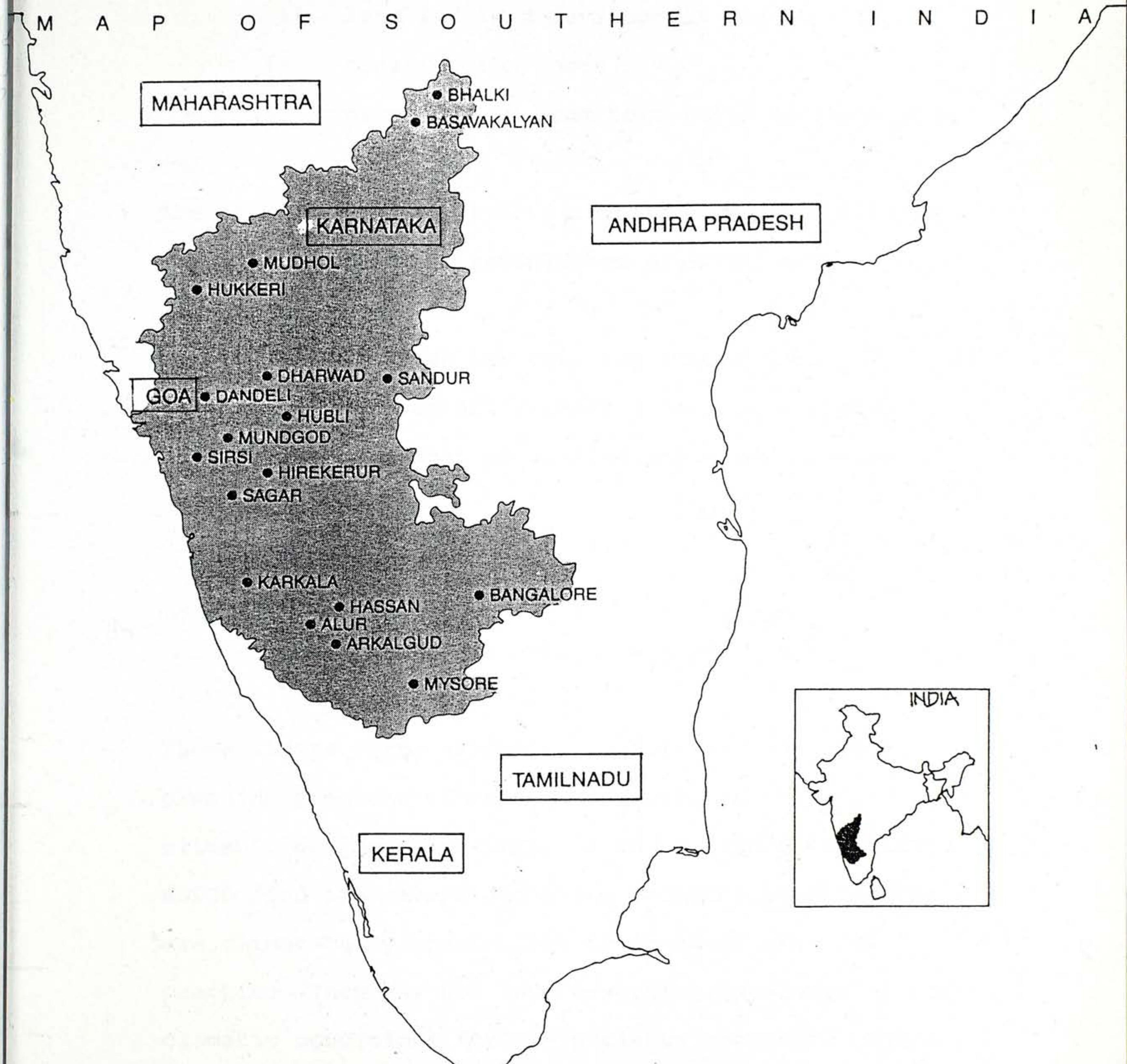

Fig. 1: Map showing locations of some of the HUDCO assisted housing projects in the southern state of Karnataka, India.

the least subsidies for the high-income group housing schemes. Subsidies include:

i) land and land development costs

ii) construction costs

iii) provision of long term loans on easy terms.

The other important architectural design considerations for which limits are established by HUDCO at the outset are:

- maximum areas per unit (by income group)
- minimum internal room areas and room widths,
- a fixed number of housing units for a given housing type,
- housing density

  and
- income group mix within each project.

These limits serve as design guidelines and help define planning problems. There is, however, an absence of climatic design guidelines. Often architects appointed by HUDCO find themselves designing projects at sites that are climatically remote from their usual area of practice. They may not have a working knowledge of the climatic conditions for the projects concerned. Added to that is a common problem encountered by the architects, which is a lack of sufficient design time. Very often when a project is handed over to an architect, it is done with a time limit of less than three months for design completion. In this period site surveys, final design drawings and estimates all have to be submitted for the Housing Boards to proceed with the next stage of project implementation, such as calling for construction tenders.

Therefore, one will find a good number of architects who are, unless they have had some experience in designing for the particular local climate, unable to utilize many of the more cost-effective strategies and affordable aspects of climatic design. Appropriate orientation, shading devices, wall thicknesses, opening sizes and their location, etc., promote an increase in comfort levels within a built space (Evans, 1980), (Rapaport, 1969), (Razak, 1992). It requires considerable investment in time and effort for practicing architects to research these critical aspects of architectural design for a variety of climatic regions.

During his years working on such projects for an architectural firm in Bangalore, Karnataka, the author felt the need for a quick reference -- a 'ready reckoner'[3] -- for climatic design that utilized existing materials and methods of construction for such climates as are to be found in the region.

3. 'Ready reckoner' - colloq., for 'quick reference' - author.

Karnataka, formerly known as Mysore, lies between latitudes 12°N and 18°N (Fig. 1a). It has four climatic zones (Koenigsberger, 1974):

i) A short 300 km. long, 80 km. wide coastal belt with a *warm humid climate,*

ii) a 1500 m. high mountain range running parallel to the coast known as the Western Ghats with a *tropical upland climate,*

iii) a 900 m. high plateau to the southern region with a *temperate monsoon climate*

and

iv) a 500 - 700 m. high plateau in the northern region with a *hot dry monsoon climate.*

This fourth zone covers approximately half the area of the state and is shared by two other states - south-eastern Maharashtra and western Andhra Pradesh. This zone is considered to be economically backward. It is in the process of receiving encouragement for agricultural, small and medium scale industries by the central as well as the states' respective governments. Housing logically forms part of the infrastructure necessary to ensure the successful implementation of the agricultural and industrial development programmes.

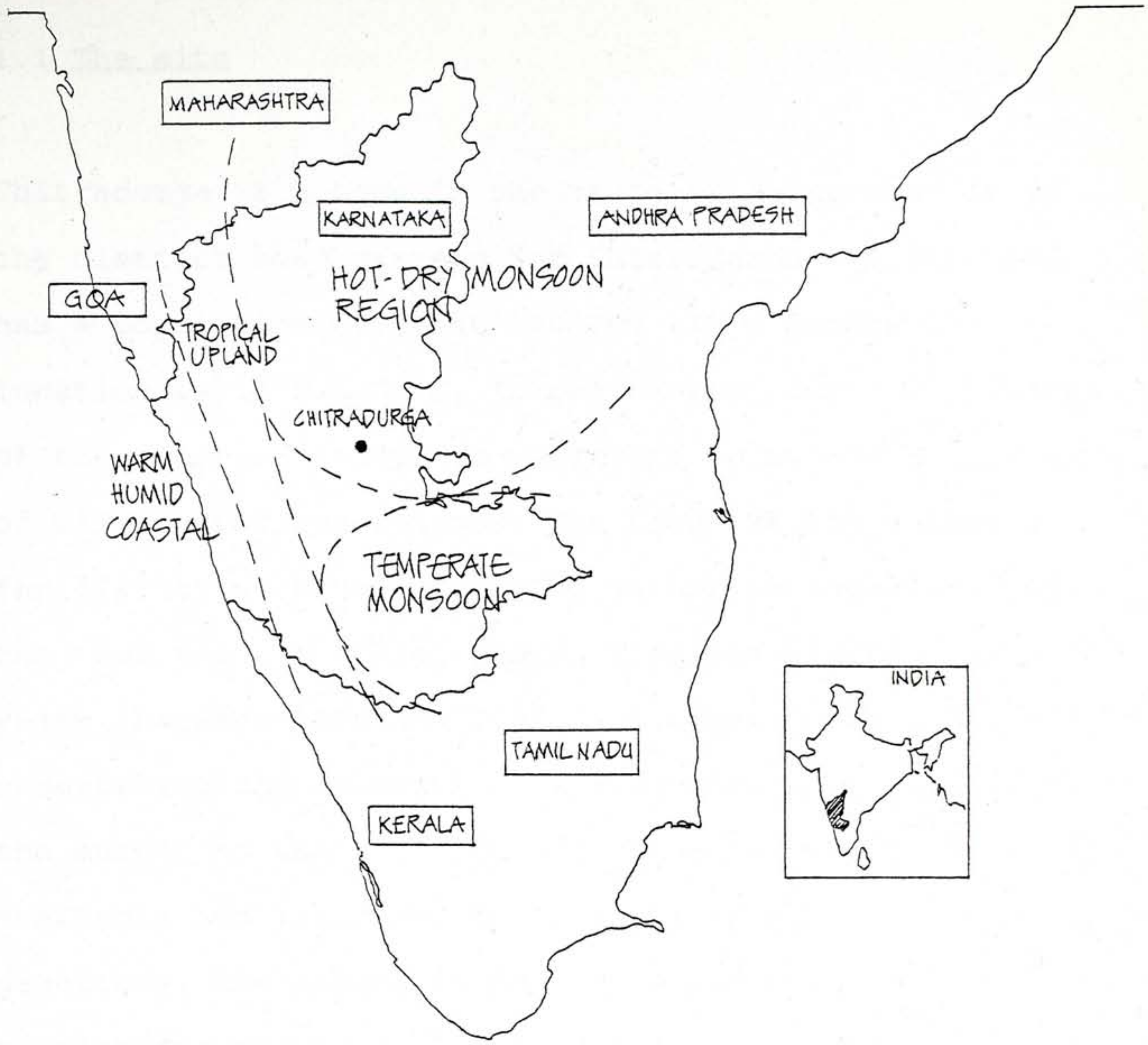

Fig. 1a: A map of Karnataka showing the climatic zones.

It is hoped that improvements, however small, in climatic design for this region, will have a cumulatively positive effect on the lives of a great number of inhabitants[4]. It was therefore proposed to study the effects of the hot dry monsoon climate upon low rise housing for middle and low income groups.

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4. Loans sanctioned by HUDCO in 1994 amounted to the equivalent of US$40 million. This would translate to approximately 15000 residential units - author.

1.1 The site

Chitradurga is a town in the state of Karnataka. It is the district headquarters for Chitradurga district and has a population of about 300,000. It's geographic location is 14°N & 77°E. It was chosen, for the purposes of the proposed study, *to represent* a town with this type of climate for two reasons. The first is the author's familiarity with the area. The author is acquainted with the town and its surroundings. Frequent visits over many years (between 1986 and 1992) while designing homes and undertaking the renovation of a nursing home have lent the author an understanding of the climate, the materials available and labor-intensive local construction practices. The second is the KHB's proposal for a housing project for the town. Approximately ten hectares of land on the outskirts of this town has been allocated by the KHB for proposed development into middle and low income group housing on the outskirts of this town.

1.2 Low rise housing for Low and Middle income groups (LIG & MIG)

HUDCO divides its housing projects into four major categories (HUDCO, 1987) - (Appendix F):

i)	Economically Weaker Sections	(EWS)
ii)	Low Income Group	(LIG)
iii)	Middle Income Group	(MIG)
iv)	High Income Group	(HIG)

Low and middle income group housing form the larger proportion of public housing projects. Over the years a form of low and middle income group housing that has proved attractive to home owners has been an 'incremental development unit' that utilizes the core-house concept (Colquhoun & Fauset, 1991), (p.45, Koenigsberger et al, 1971). As the name suggests, the construction of the unit is implemented in stages, initially appearing as a LIG housing unit that, over a flexible period of years based on a family's economic necessity and growth develops into a MIG unit. This growth is not irregular but is based on the architect's designs for the unit.

The growth is represented in five stages (Figs. 3 - 8). A convenient pattern of development is the row housing pattern represented below (Fig. 2). [This is a simplified representation only and, is non-specific with respect to orientation as, under actual site conditions a given unit may face any arbitary direction.]

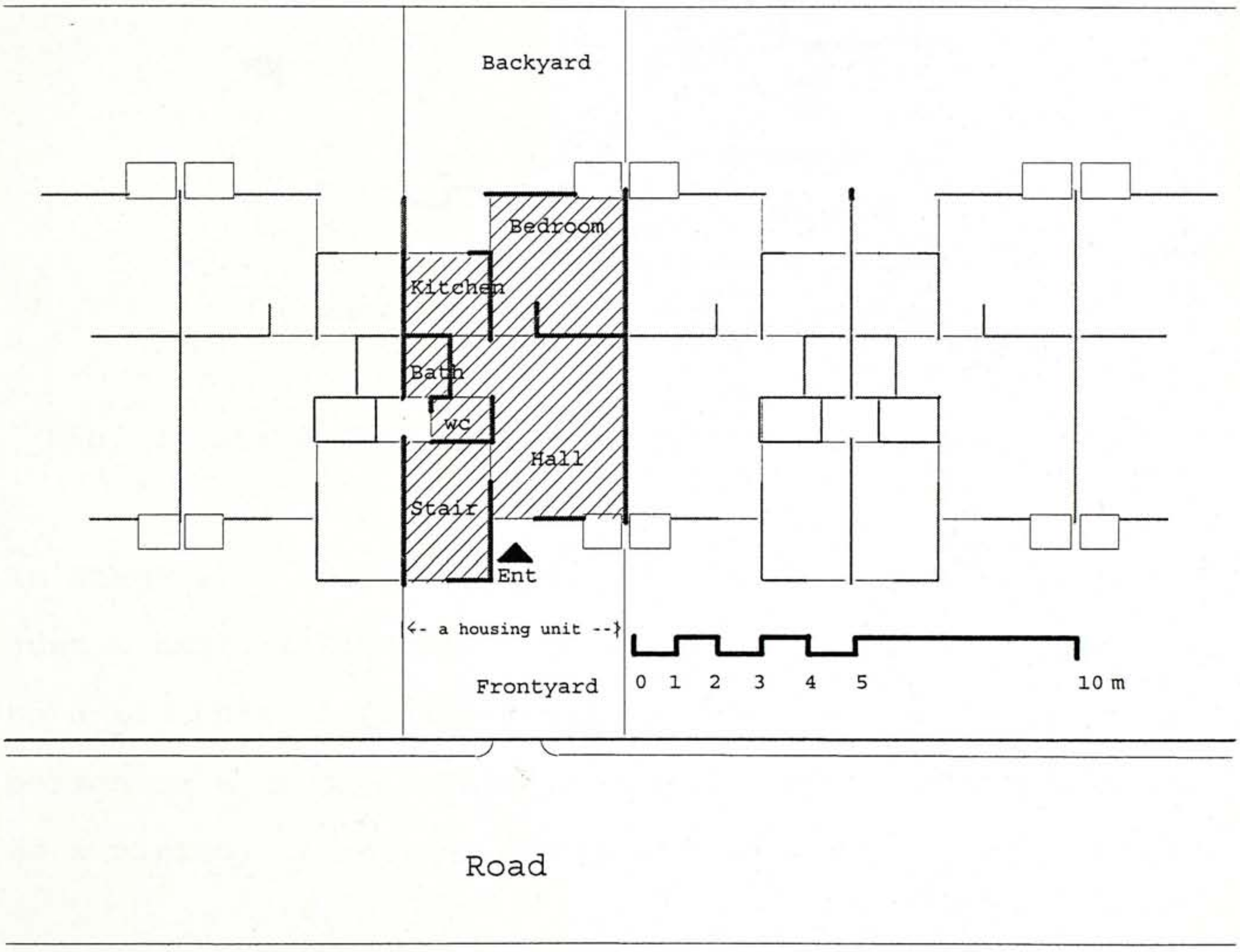
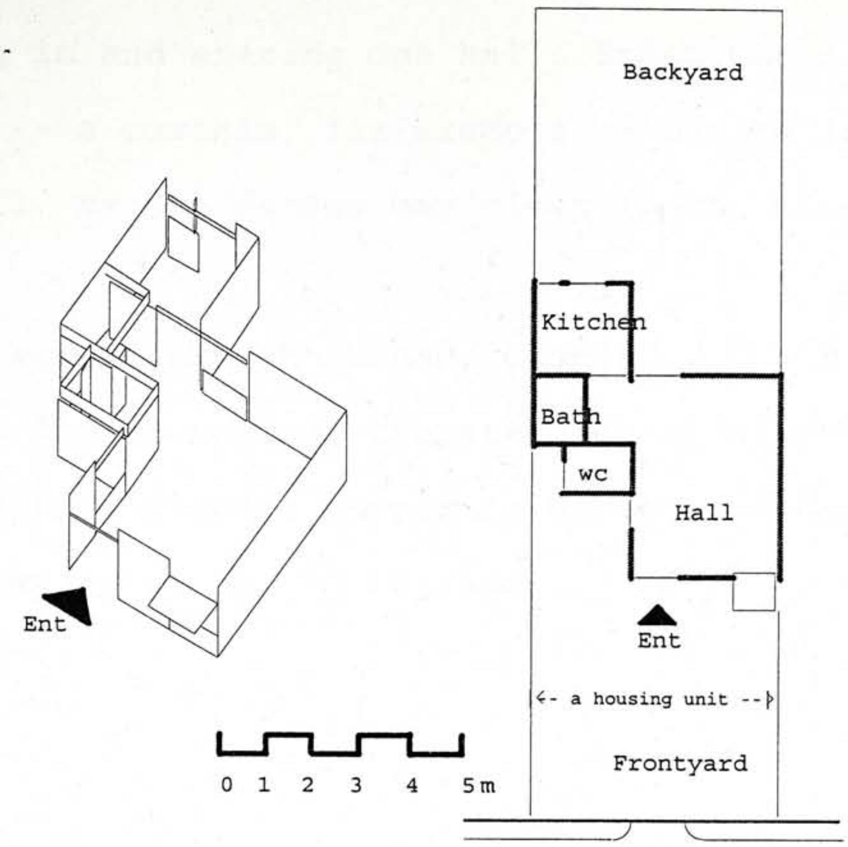


Fig. 2: Part of the cluster that forms row housing.

The descriptions following each figure are of a very general nature, considering the many possible circumstances that go with a family's growth and the patterns of living.



The basic LIG unit - in view and on plan

Fig. 3: Stage I of an incremental development MIG unit

In Stage I, a very basic MIG unit is built that includes just a hall, a kitchen, a bath and a toilet. This is akin to a LIG unit. A family moving in may consist of just one person or a couple. (This is a very general assumption, as a variety of options are possible):

- a couple moving in may have a child or children;
- in some cases a relative may join in;
- the house may be let out till the family is ready to move in.

In short, it is not unlikely to have three or four people residing in this small house even at this early stage, all living in and sharing one hall. Sometimes a temporary partition -- a curtain, for example -- may be introduced in the hall, or one person may sleep in the kitchen.

Lack of space within the house, coupled with the relatively cooler outdoor temperatures at night during the hot season, induces people to sleep outdoors, either in the backyard or on the terrace.

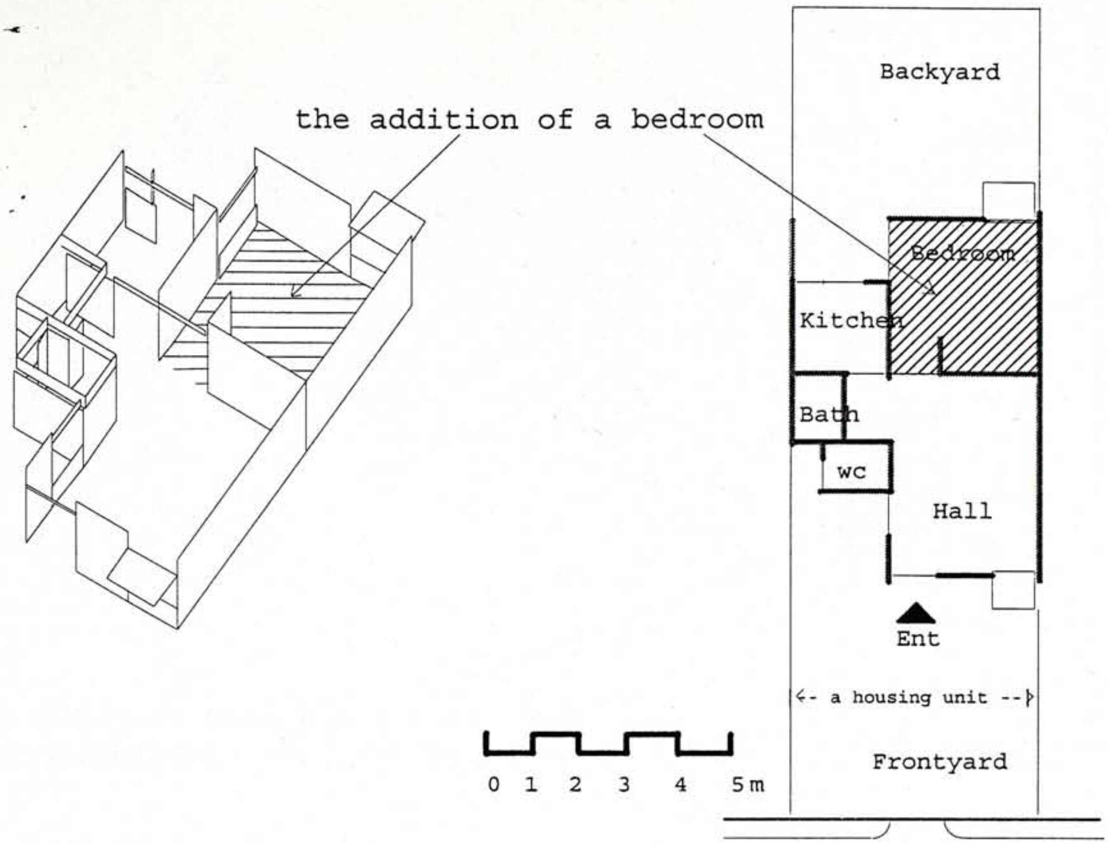


Fig. 4: Stage II

Stage II may occur a couple of years after stage I. A very important addition, a bedroom, appears. The family at this stage will usually consist of a couple with one or two children. The addition of this room greatly reduces the stress of many people living in just one hall.

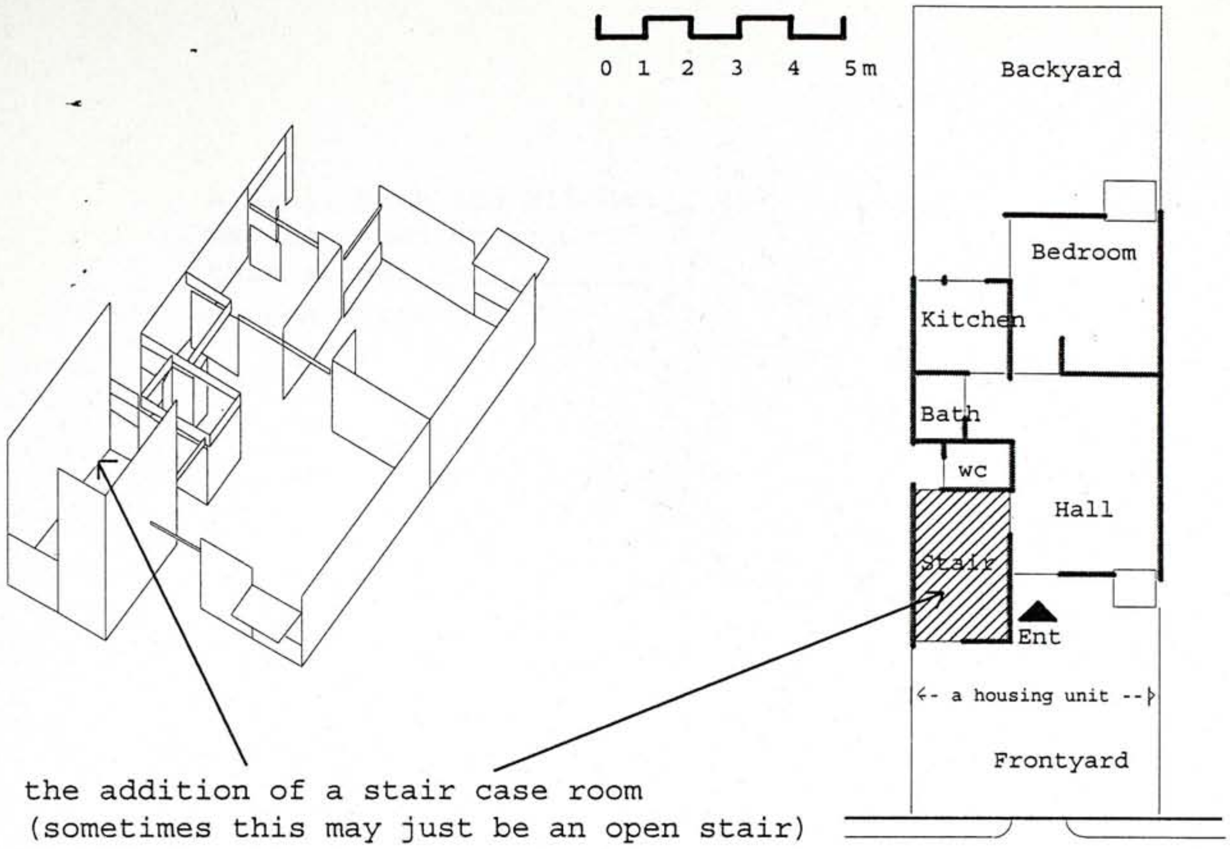


Figure 5: Stage III

Stage III usually occurs between five and ten years after stage I and involves the building of a staircase (in many cases this may be just a flight of steps open to the exterior), just a hall on the first floor and a second toilet. The housing unit would now begin to resemble an MIG unit. A pair of units (Fig. 6) shows how they appear:

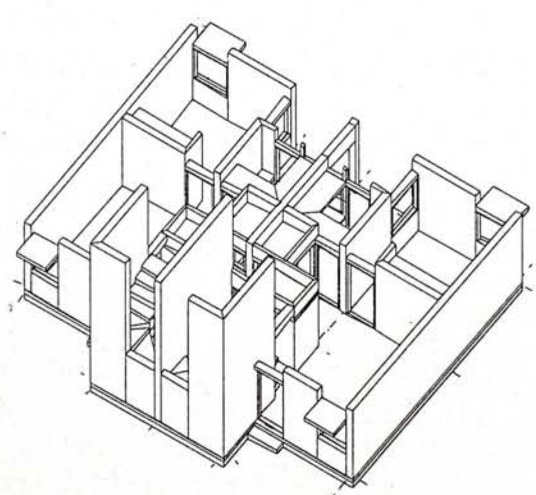


Fig. 6: Axonometric view of twin units.

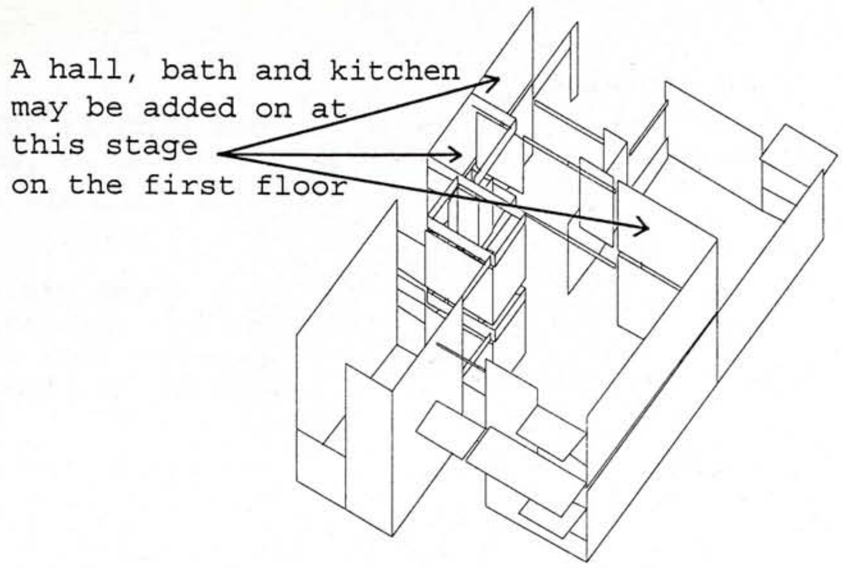


Fig. 7: Stage IV

In stage IV a second kitchen on the first floor may allow the first floor to be rented out to a separate family, or in case parents move in, the couple may move upstairs. This would allow their parents the convenience of living on the ground floor. This stage usually occurs at around ten to twelve years after stage I. One of the children may be old enough to go to college (and so may move away to a hostel) or may move to a different town in search of work.

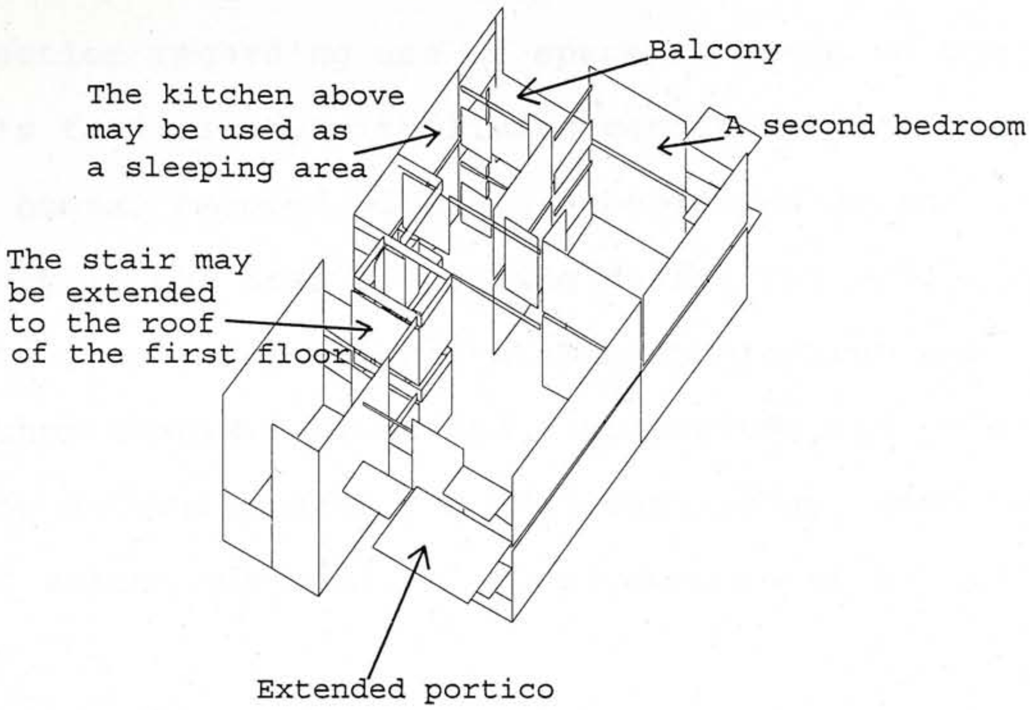


Fig. 8: Stage V:

Stage V represents the completed housing unit, a repeat of the complete ground floor unit on the first floor, an extended portico, balconies at the rear to provide some semblance of an 'outdoor' space, and the possible continuation of the staircase to the roof of the upper unit. If the whole house functions as one, then the kitchen space on the first floor may also be used as a sleeping area.

1.3 Use of space with respect to time

This section regarding use of space is based on the author's familiarity with living conditions in south Indian homes, coupled with his experiences as an architect in the area of housing design for HUDCO. An activity chart (Fig. 9) has also been prepared based on the author's observations and a comparison can be made with the activity chart for Khartoum, Sudan, also during the hot season (Appendix A, Koenigsberger et al, 1974).

Families tend to include three to four adults and two to three children (the husband and wife, the husband's parents, two to three children, and maybe one or two relatives) for a total of six to eight people living in a two or three bedroom house; this number is quite common among low and middle income group families (Saini, 1980). The husband is the main wage earner and the wife generally manages the household, with some duties divided between the grandparents. If the wife also works, the house may be managed by the grandparents. Children attend school from the age of six onward.

Generally children are first to leave the house for school in the morning, usually before seven. The husband leaves early for work around the same time only if he works in an industry, on a farm or if he has a shop to run, otherwise most offices open around nine to half past nine.

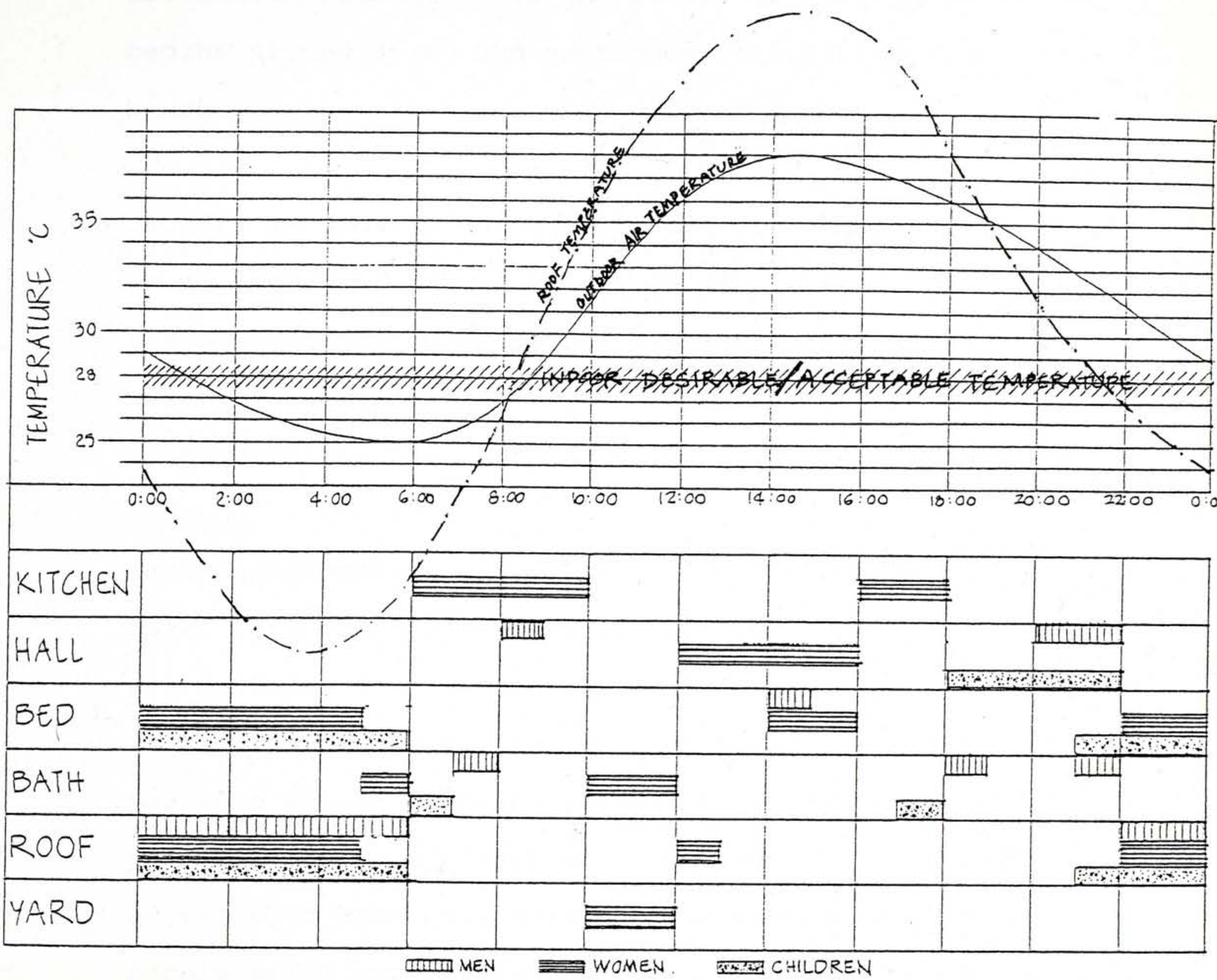


Fig. 9: Activity chart for homes in Chitradurga, south India (based on the author's observations).

There is a great deal of activity early in the mornings as most households of four to six people have just one toilet and bath. For this reason toilet and shower areas are seldom combined into one facility. Food preparation begins around 06:00 and continues till around 10:00 hours.

Laundry is usually an outdoor activity. Mopping of floors is an important activity that serves to cool the rooms by evaporation and helps reduce dryness in the air (Saayigh, 1991). Sprinkling of water on the front and back yards helps keep the dust down as well.

Early afternoons (between 13:00 and 15:00 hours) are quiet periods with sedentary activity at best. Few people are at home. Those who are usually are at rest. Children get back from school around 16:00 hours and the family is reunited around 17:00 hours. Visitors may drop in or people may choose to go out in the evening. Generally everyone is back home before 21:00 hours for dinner. Many people watch popular television programmes[5] after dinner time. Children may be asked to do their homework. Everyone generally goes to bed by around 23:00 hours.

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5. This is only from the mid-1980s onward; the network of television broadcasts in India was upgraded to cover the whole country around this time. In addition to this, STAR TV was introduced in 1990. Its success confirms the fact that more people stay at home to watch TV than before.

1.4 Adapting for comfort

Air conditioning is not used as it is not affordable; hence adapting for comfort by the inhabitants (in other words, not gaining heat) during the hot season takes the following simple forms, termed as 'managerial control' (Koenigsberger, 1974).

- Ceiling and table (or pedestal) fans become necessities to improve air circulation, promoting heat loss by convection and evaporation (Chow & Fung, 1993).
- Windows may be kept closed during the day to keep out bright light, hot air and dust; and may be kept open at night to help the house lose heat to the cooler outside. This promotes heat loss by convection (Fathey, 1986).
- People walk barefoot within the house. This promotes heat loss by conduction to the floor (Fanger, 1970).
- On hot nights, sleeping outdoors is not uncommon. (This promotes heat loss by convection, radiation and evaporation). (Adebayo, 1990).
- Clothing is light (0.25 - 0.5 Clo[6]). (This minimizes heat retention). (Givoni, 1976).

6. Clo: A unit of thermal resistance of clothing. (A Clo value of 1.0 represents a standard two piece business suit and accessories. A pair of shorts is about 0.05 Clo - Appendix B.)

1.5 The roof as a sleeping area

The hot dry season also brings with it temperature swings of over 15°C (ISRO, 1993). This means that outdoor spaces during the night become acceptably comfortable in terms of temperature. Very naturally, people have for ages used private outdoor areas such as front and back yards, courtyards, balconies and flat roofs[7] as sleeping areas (Adebayo, 1990). Of these, courtyards are usually the most private of outdoor spaces. A sense of privacy is also achieved when roofs are used for night time sleeping.

The common method of sleeping up on the roof is to first create a place to sleep on by unfurling a straw mat upon the roof and then unrolling a cotton mattress upon it. Often, a couple of folded blankets may be used in lieu of

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7. Flat roofs are commonly built as follows: Once the load bearing walls for a room or a set of rooms are built to roof height, scaffolding is erected. This is usually out of a commonly available source of timber, which in these regions is either the *cashewrina* tree or the *silver oak* that provides 100 - 150 mm diameter and 4 - 5 m long sturdy poles. These poles are spaced at around 0.6 - 0.75 m in either direction. The top is framed together with a network of minor branches and grass and weed are used to fill the minor spaces. This is formed into an even surface using plain earth. Once this surface is tamped it may even be "smooth-finished" with cement slurry or even cow dung. This process is termed "mud-centering". Reinforcment steel (usually one-way, as the spans are generally not greater than 3.6 m) for concrete is laid upon this centering. Coarse aggregate is used here and there as spacers below the tension bars in order to ensure a bottom cover for the concrete roof. After the concrete is poured and set (usually to a thickness of about 150 mm), a layer of brick bats is laid on top varying from about 200 - 230 mm thickness at the centre to about 75 - 100 mm thickness at the edges. This is covered by a layer of lime mortar laid to a slope of at least 1:60 to ensure drainage of rain water. The above process is widely used in the construction of flat concrete roofs - author.

a mattress. If mosquitoes pose a problem then mosquito nets are used over the sleeping areas.

The author has had some experience with sleeping up on the roof. While it is reasonably comfortable at night, a feeling of being quite cold occurs around 03:00 or 04:00 hours, just before dawn. People either reach for an extra blanket at this time or simply roll up the bed and go back into the house carrying it with them. Depending upon their routine they may continue to sleep inside or begin a new day.

During these pre-dawn periods temperatures drop to around 15°C for a brief duration. There are no measurements of roof surface temperatures available to the author but the roof was felt to be quite cold to the touch. This is because of continuous radiation losses to the night sky as the skies are extremely clear during this season. Clear, night sky temperatures range from -20 to -25°C at the zenith of the sky vault, to roughly the air temperatures at the horizon (Higgs, 1991). Flat roofs see most of this cold sky all night and being at a higher temperature lose heat all the time with little gain from the immediate surroundings until an hour or so after sunrise. Also, the presence of parapet walls means that long shadows will be cast upon the roof for the first hours after sunrise and the roof may begin to heat up from the sun's radiation only after around 07:00 hours.

2.0 Objective

The aim of this work is to create a climatic design checklist, a sort of a quick reference for designers working on projects situated in the hot dry monsoon regions of south India. These design guidelines should cater to those elements and spaces within that make up a typical low-rise, Low and Middle Income Housing unit, namely:

i) orientation

ii) walls - their thickness, material and color

iii) openings - their size and placement

iv) roofs - their material, thickness and colour

v) shading components - their size, placement and effectiveness

3.0 Methodology

Many researchers have created and explored a variety of methods for predicting comfort levels for an unbuilt design. Computerized thermal modelling is one of the methods. Many such thermal modelling systems exist today. Some of the more prominent ones (Appendix D) are:

i) Building Load Analysis and Systems Thermodynamics program (BLAST) developed by the US Army Construction Engineering Research Laboratories, US (Littler & Thomas, 1984).

ii) Dynamic Energy Response Of Buildings (DEROB) developed at the University of Austin, Texas (Higgs, 1991), (Hand, 1987).

iii) the US Department of Energy's DOE developed at the Lawrence Berkeley Laboratory, US (Chow et al, 1993).

iv) the Environmental System Performance program (ESP) developed at the University of Strathclyde, UK. (Clarke, 1985)

Running such software on powerful computers allows one to quickly model a building for a given location and climate, all the while employing many different and comparative scenarios.

A study using DEROB was performed between August and October 1994, for a type of apartment for Hong Kong's high rise public housing (Higgs, 1994) to assess its thermal performance during the hot period that lasts from April to October. Apart from the time spent creating data files, a full run typically took about two and a half hours for 32 variations in location when run on a Sun Sparc 10/50 workstation. This sort of generous computing power was available to the author during the latter half of his research period.

The DEROB system has the following advantages:

i) It has a very general structure allowing for **high reliability** in a variety of situations.

ii) It is very **'first principles'** oriented and has a compact, well documented kernel consisting of less than 10000 lines of FORTRAN coding.

iii) Unlike most other simulation systems it employs **few simplifications** for the sake of run time efficiency.

iv) It is not encumbered with "engineering models" of variables interactions where the limits of the models are not well understood.

v) The **source code** is readily available. Access to the internal workings of DEROB by a knowledgeable programmer greatly extends the usefulness of the system.

An added advantage is that the DEROB system has been set up such that it can be run both as a MSDOS based application or as a UNIX based one *and* allows for a ready interchange of information. The author's earlier familiarity with MSDOS allowed data files to be created using simple text editors as required by DEROB and making test simulation runs on a 80486 based PC. The tested inputs were then transported to the much faster SUN SPARC 10/50 workstation for sensitivity studies.

Field validations have been carried out on DEROB at the Los Alamos Scientific Laboratory, New Mexico, (Arumi-Noe & Northrup, 1979), as well as comparative field validation studies with other simulation systems (Judkoff, et al, 1981). The program has been shown to be capable of reproducing observed measurements consistently, within a 5% margin (Arumi-Noe & Northrup, 1979).

The results of experiments in DEROB with on site readings have been well documented and referred to in various studies (Littler & Thomas, 1984), (Higgs, 1991). It can now be used as a tool for predicting the thermal behavior of a building for a given location provided reliable climate data is available.

3.1 DEROB - An overview

DEROB, or Dynamic Energy Response Of Buildings (DEROB-IUA, 1984) is a computer program that is used as a simulation tool to model the thermal behavior of the elements and the spaces within that make up a building within a given weather framework. The DEROB suite of seven component programs is a building shell intensive thermal simulation model. It reduces a building's description to a R-C network (Resistance-Capacitance electrical network) analogy and then proceeds to solve the network for hourly weather conditions.

The component programs require input regarding:

1. The geometric and material descriptions of the building's various elements: floors, walls, openings and shading components
2. The building's orientation, period of the year for the simulation, information on mechanical equipment used to control indoor climate (if any), all other energy inputs within the building
3. An hourly weather file for the location in consideration.

The output is in the form of a report on the building's thermal performance.

The component programs that make up DEROB are:

Program:	Deals with:	Requires:
DIG (Digitization of building geometry)	-Solids and voids that make up a building	a. Building geometry input; may also require b. additional information regarding advection connections between internal volumes c. fluids contained by the volumes, if not air
GF (Geometric factors)	-Geometric view angle factors between planes	- Building geometry input
WAL (Wall equations)	-Properties of opaque walls	- Wall materials, their order of placement and thicknesses
LUM (Luminance tensors)	-Opaque wall surface absorptivities and transmissivities	- Surface absorptivity input in solar and IR bands
SOL (solar penetration)	-Orientation and simulation period	- Building's orientation with respect to south, simulation start and end time & moveable insulation schedule, if any
TL (Thermal loads)	-External & internal climatic conditions	- Thermal loads: thermostat settings, ventilation capacities, schedules and connections, weather file

The DEROB-IUA 1.0 flow chart (Fig. 10) further clarifies the working of the system. The output of one component program is read in as the input for another. This works well for the user. Once a building's description is set up and a set of studies is carried out, one needs to run just the last two modules (SOL and TL) in case only the effects of orientation need to be studied. If one changes wall materials, just the WAL and TL modules need to be run again. If absorptivities are changed, just the LUM and TL modules need be run again.

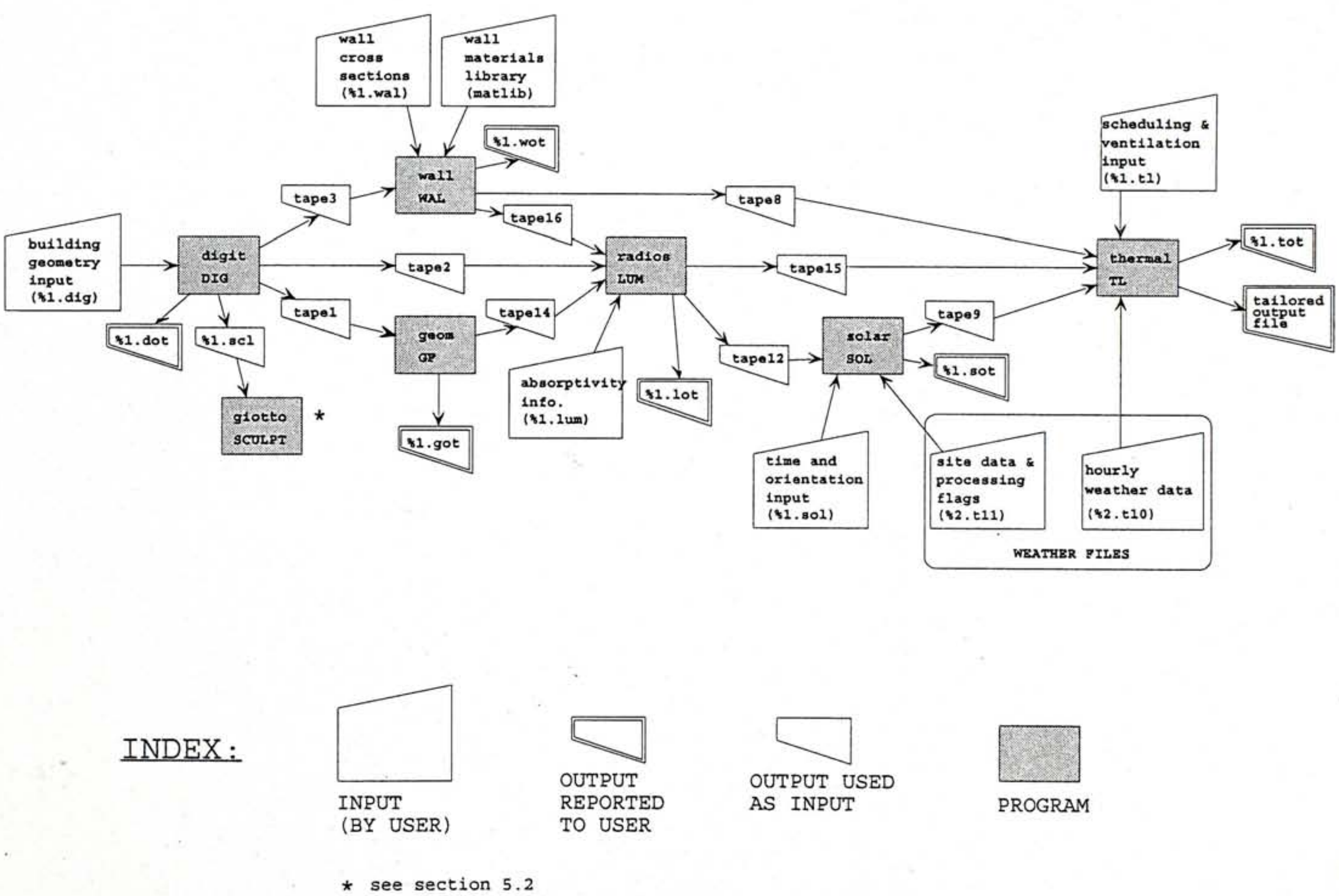

Fig. 10: DEROB IUA 1.0 Flow Chart.

Specialised output file statements in the TL file settings allow the user to save specific results apart from the standard output generated by the TL run. If the resultant temperature, or the energy balance in the form of radiation (IR or solar), convection or conduction energy for a particular volume or surface for a particular hour is required to be saved to a file, it can be done so from the TL run.

3.2 Modelling the climate

3.2.1: The climate of Chitradurga district is marked by three different seasons (ISRO, 1993):

a) *A hot dry season*: This occurs between March and May during which the mean daily maximum temperature reaches 38°C and the mean daily minimum is 25°C. During this season maximum temperatures may reach 41°C. Skies are clear throughout. Relative humidity is around 65% in the mornings, dropping to below 30% in the afternoons. This implies a dewpoint average of around 18°C. Winds are very slight, and are rarely more than 2 meters per second.

b) *A relatively pleasant monsoon season*: Annual rainfall on an average is around 580 mm. This occurs mainly between June and September. There is also a second short monsoon with similar conditions between mid-October and mid-November. On an average there are 40 rainy days in a year. The monsoons are accompanied by moderate winds averaging 4 meters per second, generally from southwest to northeast.

c) *A cool dry season*: December to February is the cool dry season with clear bright weather. The mean daily maximum temperature is 28°C and the mean daily minimum during this period is a relatively cool 17°C.

It can be seen from the weather data gathered for Chitradurga district (Appendix E) that the most problematic period with respect to human comfort is the hot dry season between March and May (Fig. 11). These three months will be taken into consideration for concentrated study.

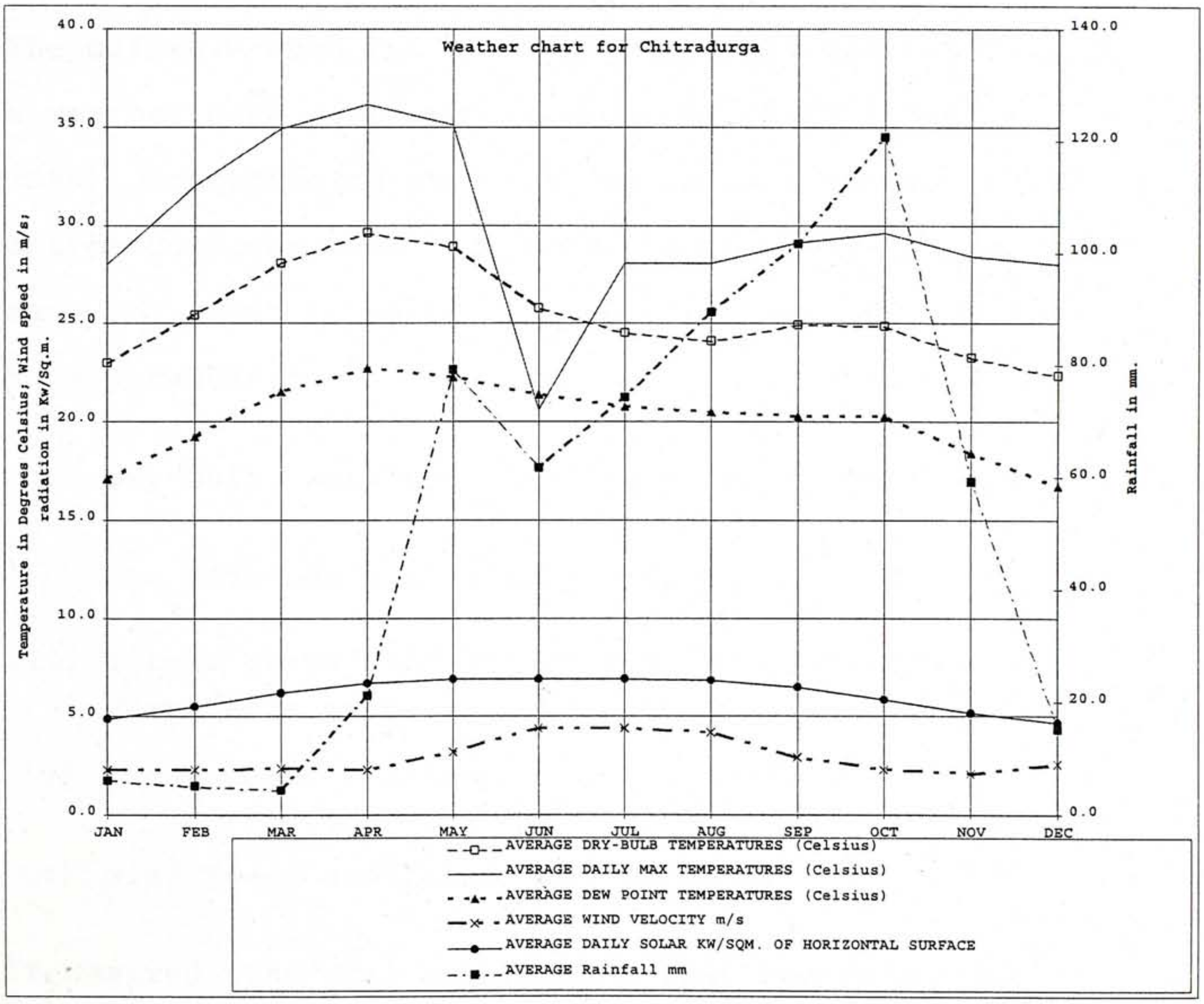

Fig. 11: Weather chart for Chitradurga.

3.2.2 <u>Modelling the climate</u> for DEROB.

DEROB requires an hourly weather file for the location in consideration. Weather data for Chitradurga district was obtained from the only meteorological observatory in the town of Chitradurga that has maintained meteorological data since the turn of the century.[8]

The software used for writing the hourly weather file is a weather data generator known as WETHRGEN (Degelman, 1990). According to their manual it is a statistically driven computer model for preparing hour-by-hour weather data for input to energy analysis software. It prepares hourly values for:

i) dry-bulb, wet-bulb, and dew point temperatures

ii) sun altitude and azimuth angles

iii) direct normal and direct & diffuse horizontal components of solar insolation

iv) cloud cover fraction

v) wind speed and barometric pressure.

If desired, the user may request that the output be written in TRY (Test Reference Year) or TMY (Test

---

8. The author had considerable difficulty in obtaining the data as he was resident in Hong Kong and had to rely on his contacts back home to procure the necessary information. This difficulty was because of the specific nature of the data required. The problem was finally solved when the office the author formerly worked for in Bangalore, a few good friends and the Scientific Secretary of the Indian Space Research Organization (ISRO) at Bangalore were approached. Much of the data received was meticulously copied from the meteorological offices by hand (Appendix E).

Meteorological Year) formats for easier input processing by other energy analysis software. If required, there is a compressed set of weather data statistics from a pre-existing weather database of two hundred and seventy one U.S. cities. The user may create a customized data base by adding any number of data sets for new sites. New sites require a "one-time only" input of about a hundred values to represent the compressed weather data. Data may be entered or extracted in either SI or inch-pound units.

For those cases where energy calculation time considerations are critical, reduced output may be selected for as few as seven days per month. These condensed outputs will still yield statistically correct weather averages and extremes for both design and energy calculations (Degelman, 1991).

The following data were input:

i) Dry bulb average for every month,

ii) Dry bulb average of maximums for every month,

iii) Dew point averages for every month,

iv) Highest maximum temperatures recorded for a month, for all twelve months,

v) Average solar radiation on horizontal surfaces by month

and

vi) Wind speed average for every month.

These averages themselves were drawn from ten years of data taken between 1984 and 1993. Perusal of the data required that dew point temperatures be obtained from relative humidity values as:

$$RH = \frac{VP_{actual}}{VP_{saturated}} \times 100\%$$

(where RH = Relative Humidity

VP_{actual} = Actual vapour pressure

and $VP_{saturated}$ = Saturated vapour pressure)

We also know that, by definition, at dew point:

actual vapor pressure = saturated vapor pressure.

This is defined as the solution $t_d(p, W)$ of the equation:

$$W_s(p,\ t_d) = W$$

which is

$$p_{ws}(t_d) = p_w = (pW)/(0.62198 + W)$$

where W_s = *saturated vapour pressure*

p = *total pressure of moist air*

t_d = *dew point temperature*

W = *humidity ratio of moist air*

$p_{ws}(t_d)$ = *saturation vapour pressure at dew point*

and p_w = *water vapour partial pressure of moist air*

(ch. 6, ASHRAE Handbook, Fundamentals, 1985)

Alternatively, the dew point temperature can be calculated directly by the following equation for the temperature range 0 to 70°C:

$$t_d = -35.957 - 1.8726 * \log_e(p_w) + 1.6893 * [\log_e(p_w)]^2$$

where t_d is the dew point temperature in °C

and p_w is the water vapor partial pressure in kPa.

(Dew points can also be read off a psychrometric chart.)

Once these required values are entered into the WETHRGEN program, the process of creating a file containing weather information for an entire year is fairly simple (a year is simplified as consisting of 365 days x 24 hours per day = 8760 hours). Customized output tailored for use with DEROB is generated. A small file describing the site's location (latitude, altitude and time difference with respect to the time meridian) and year or period of study is also required.

After the DEROB weather file for Chitradurga was created, random comparisons were made with the actual weather data for a few different days in a year and the results were consistent with the pattern of variation though not necessarily corresponding to the actual entries recorded hour by hour[9]. (Compare the sinusoidal curves from an actual day with one generated by WETHRGEN in Fig. 12.) This is to be expected as, similarly, even actual weather data from any two years for a given location would only show consistency with the pattern of variation.

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9. A "mismatch percentage" with respect to variations from an actual day to a corresponding Wethrgen generated day can probably be deduced provided there is enough recorded hourly weather data available for a great number of days.

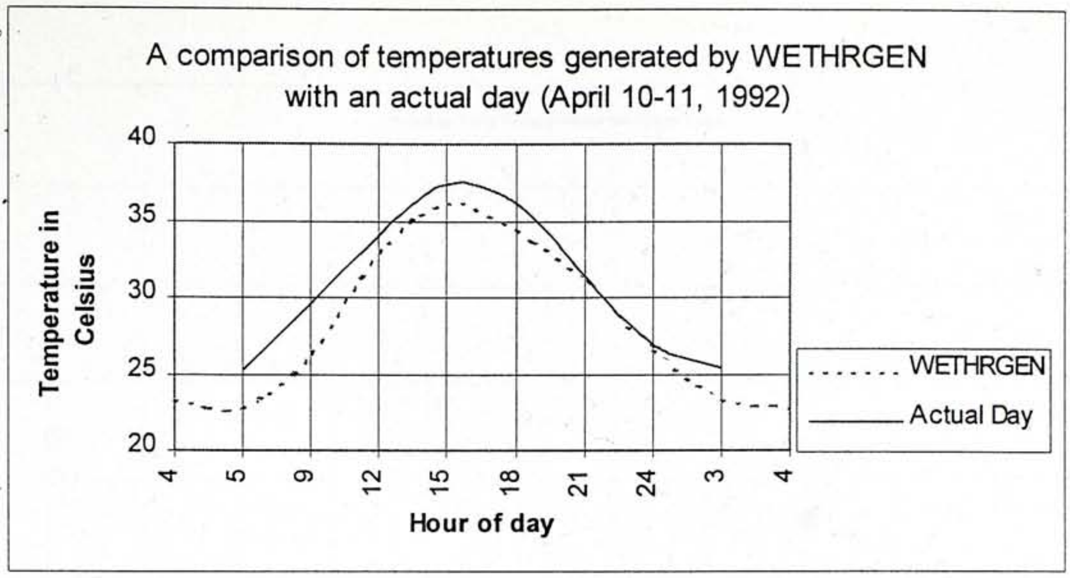

Fig. 12: A comparison of diurnal temperature curves

A further observation regarding the weather file was made. The daily averages were plotted on a graph (Fig. 12a) and there appears to be a monthly pattern followed by Degelman's software in compiling the weather file. There is a marked fall and a sharp rise between the last day of every month and the first day of the next. Although this kind of variation in daily averages is not abnormal in real life situations, the pattern seems to be unusually consistent. There remains a doubt in the author's mind regarding the efficacy of this method of weather file generation[10]. However, in the absence of any other weather file generating program known to the author, this one is used.

10. Section 3.2.3, which follows, explains how a weather file thus generated, (discrepancies included) can be manipulated for the purposes of studies like this.

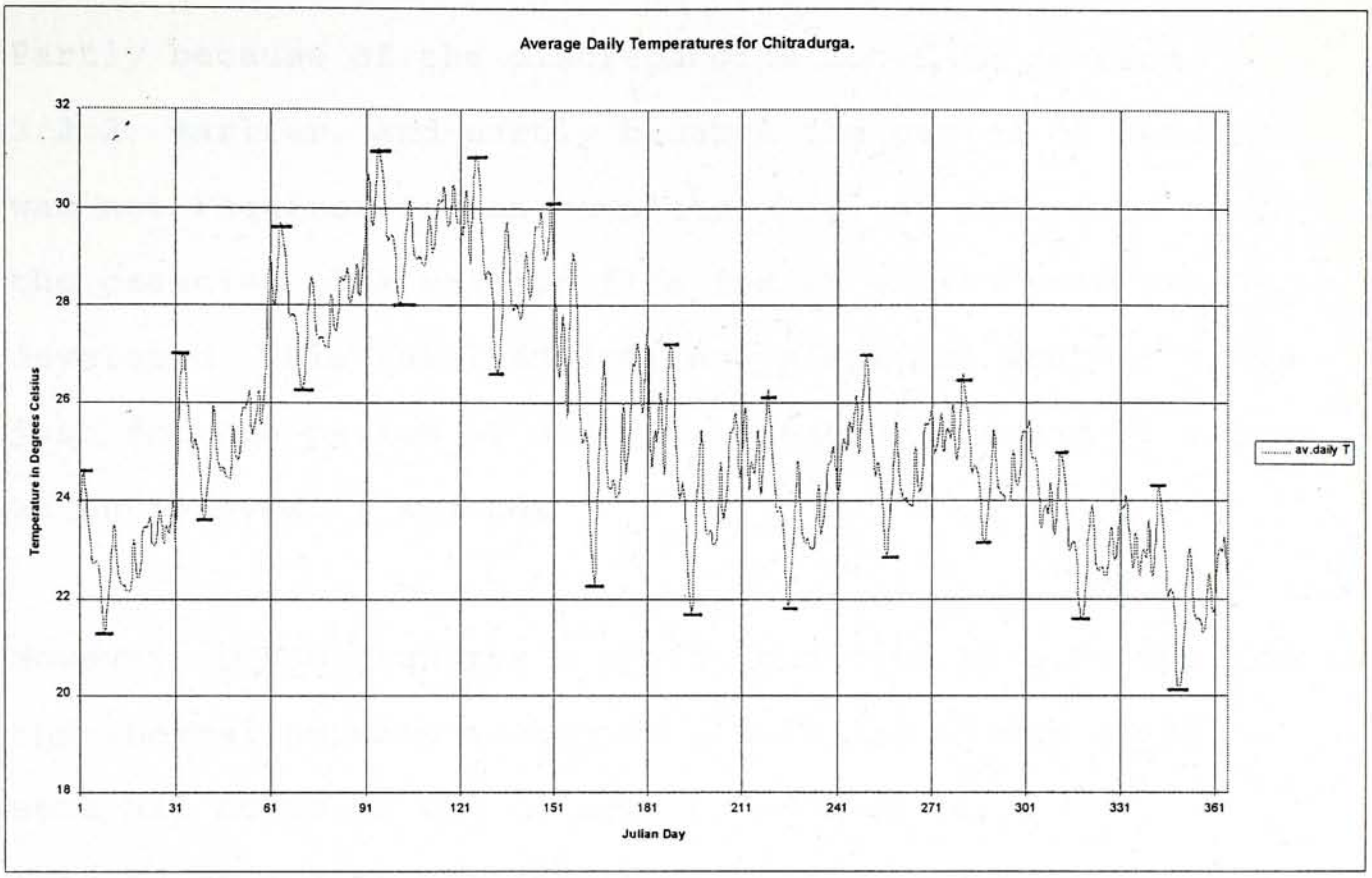

Fig. 12a: Averaged daily temperatures as generated by Degelman's Wethrgen software showing the repetitive and unnatural 3°C fluctuations by month

3.2.3 Special weather files

Partly because of the discrepancies noted in section 3.2.2, earlier, and partly because the period of study was not required for an complete year, an extension to the creation of a weather file for an entire year was developed. This involved setting up special weather files just for the period of study in question instead of using an entire year's weather.

However, DEROB requires a start-up period to precondition the thermal network analog of a building (since DEROB sets all nodes in the network to 20°C at the outset). This is done with the intention of "exposing" the computer model to the climatic conditions in question so that a simulation is started from a situation that resembles what would be encountered in practice.

According to the DEROB users' manual, in the absence of a start-up period DEROB defaults to preconditioning the building with four days of the first day's weather data. For heavy structures with reasonable amount of thermal mass[11] a longer start-up period needs to be specified. This would, however, still use just the first day's weather data.

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11. "Reasonable amount of thermal mass" here refers to buildings with at least 230 mm brick walls and 150 mm concrete roofs. A "heavy structure" is not defined exactly but it can be read here as a structure that, by virtue of its mass, contributes to a time lag of not less than 7 hours for heat transmission from one side of a barrier to the other (pp. 41, Saini, 1980).

Sometimes the studies may need to be carried out for just a few weeks[12]. One may need to concentrate on the particular nature of the weather in question (in this case the hot dry season). However, a typical month within a study period may not be composed entirely of typically hot days. To achieve this 'selectively hot, synthetic weather' (mimicking a hot spell), an algorithm was written. This program scans the entire weather file containing a year's weather data to select the top 10, 5 or 2½ percent ('x' percent) of hot days in a year. The sampling process involves calculating the average daily temperature and selecting the top 'x' percent hot days[13].

Explaining this in matrix form (Fig. 13), these are lined up in a column in ascending order one below the other. Then the average daily temperature for twenty days before each of these days is entered in each row, ending with the 'x' percentage day.

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12. Consider, for example, a building that is simulated from the first day of March to the twenty-first day of March. If a two week start-up period is included, DEROB will pre-condition the model with fourteen days of the 1st of March's weather data. It would then process the weather data from the simulation period. The report of the thermal performance of the building would still be generated just from March 1 to March 21, ignoring the fourteen repetitive days prior to March 1.

13. The top 10% hottest days would mean the hottest 37 days, the top 5% hottest days would mean the hottest 19 days, etc.

THREE WEEK STARTUP PERIOD LEADING UP TO THE 2.5% DESIGN DAY

	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	
1																					Hottest Day
2																					2nd Hottest
3																					3rd Hottest
4																					4th Hottest
5																					5th Hottest
6																					6th Hottest
7																					7th Hottest
8																					8th Hottest
9																					9th Hottest
Av																					Average 1 -> 9
																					Day in the weather file

DAYS IN THE WEATHER FILE THAT ARE CLOSEST TO THE AVERAGES FORM A SPECIALISED WEATHER FILE LEADING UP TO THE DESIGN DAY

Fig. 13: Selecting a '2.5%' percent day

The columns are now averaged out and a day in the yearly weather file is found in each case where the average daily temperature is closest to it[14]. When twenty such days are lined up in sequence, ending with the day before the average of the 'x' percentage days as the last one, a realistically intense and selective 'average of averages' three week start up period is formed.

The three week weather file can be used by itself as a stand alone weather file or it can be spliced into the

14. This means that a day in the yearly weather file may be selected more than once.

Wethrgen generated one year file for the required season. This method allows for the development of a more accurate profile for an element's thermal performance under continuously intense weather conditions leading up to the day in question - or the 'design day' - for the purposes of the study. The intensity of the period can be increased by choosing smaller values for 'x' (smaller values of 'x' will make the 'design day' closer to the hottest day in terms of average daily temperature.)

3.3 Fanger's Comfort Equation

Field studies undertaken in hot climates indicate that the acceptable upper limits for indoor air temperature lie between 28°C and 29°C (Fanger, 1970), (Saini, 1980) (Adebayo, 1990).

A comfort study among 152 Asian and European residents shows an upper limit for air temperature at 27°C, with relative humidity around 80%, and relative air velocity around 0.4m/s for persons with typical tropical clothing, estimated to have a Clo value of 0.40 (Ellis, 1952). A field study in Singapore, including 14 subjects, found, under approximately the same conditions as those examined by Ellis, an optimal temperature of 28.5°C (Webb, 1960). Other such studies have been carried out in hot-arid zones such as central Australia (Macfarlane, 1962), and hot-humid regions such as Calcutta (Rao, 1952).

One such study has arrived at average figures of 29.4°C dry bulb as the upper limits of comfort that may be considered for minimum standards of design (Campbell, 1965). Although the studies quote air temperature as the criterion (after specifying the other environmental variables), the following comment is worth noting:

> *These upper limits were mainly based on experiments in hot regions where humidity is high. In hot dry lands where there is no*

humidity problem these figures could well be higher (Saini, 1980).

The statement above is worth considering. To deliberate upon it, a derivation of the comfort equation, which is the equation for the Predicted Mean Vote (PMV), is used (Fanger, 1970). An explanation of this is given in the following section.

3.3.1 The Predicted Mean Vote

The comfort equation treats the human sensation of comfort as a function of six variables - four environmental (air temperature, mean radiant temperature, water vapor pressure & relative air velocity), and two personal (the thermal resistance of clothing worn and the metabolic activity level)[15]. Fanger's comfort equation states:

$$\frac{M}{A_{Du}}(1-n)-0.35\left[43-0.061\frac{M}{A_{Du}}(1-n)-p_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-n)-50\right] - 0.0023\frac{M}{A_{Du}}(1-n)(44-p_a) - 0.0014\frac{M}{A_{Du}}(34-t_a) =$$

$$3.4*10^{-8}f_{cl}[t_{cl}+273)^4 - (t_{mrt}+273)^4] + f_{cl}h_c(t_{cl}-t_a)$$

where $M/A_{Du}, n$ *are a function of the type of* <u>*activity*</u>

t_{cl}, f_{cl} *are a function of the type of* <u>*clothing*</u>

and h_c, t_a, p_a, t_{mrt} *are* <u>*environmental variables*</u>.

Using the comfort equation it is possible, for any type of clothing (Clo) and any type of activity (kcal/hr.m²), to calculate all reasonable combinations of air temperature, air humidity, mean radiant temperature and relative air velocity which will create optimal thermal comfort under steady state conditions (Fanger, 1970).

Satisfying the comfort equation is a condition for optimal thermal comfort; but the equation only gives information about the combination of variables required

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15. An interesting point arises here - how does one go about ranking these six variables in order of importance? After discussions with Dr. Higgs, it transpired that clo value and metabolic rate are easily the two variables we are most sensitive to; this is followed closely by air temperature and air movement. Relative humidity, because of the broad range (20% - 80%) within which we do not feel any discomfort, and mean radiant temperature, due to the fact that it is not a big variable in most normal indoor conditions, come last.

for creating optimal thermal comfort. According to Fanger, it is not suitable as is for determining the thermal sensation of a group of persons for any one kind of climate (p.110, Fanger, 1970). However, using the comfort equation as a starting point with a group of persons voting on the modified seven point psycho-physical ASHRAE scale (ranging from -3 [cold] to 0 [neutral] to +3 [hot]) Fanger established a connection between the thermal variables and the scale, such that when the comfort equation is satisfied one would expect a mean vote equal to zero (neutral). He termed this as the Predicted Mean Vote (PMV).

Fanger's equation for the Predicted Mean Vote is:

$$PMV = (0.352\, e^{-0.042(M/ADu)} + 0.032)\left[\frac{M}{ADu}(1-n) - \right.$$

$$0.35\,[43 - 0.061\frac{M}{ADu}(1-n) - p_a] -$$

$$0.42\,[\frac{M}{ADu}(1-n) - 50] -$$

$$0.0023\,\frac{M}{ADu}(44-pa) - 0.0014\,\frac{M}{ADu}\,(34 - ta) -$$

$$\left. 3.4*10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_{mrt} + 273)^4] - f_{cl}h_c(t_{cl}-t_a)\right]$$

where $M/ADu, n$ *are a function of the type of* *__activity__*

t_{cl}, f_{cl} *are a function of the type of* *__clothing__*

and h_c, t_a, p_a, t_{mrt} *are* *__environmental variables__*.

3.3.2 The Predicted Percentage Dissatisfied

The PMV is an expression for the general degree of discomfort for a group of people as a whole, but it is nevertheless difficult to interpret what the magnitude of PMV can imply for practical purposes. Therefore a more useful expression has been derived by Fanger in his study which can be readily interpreted. This expression states what percentage of persons in a group can be expected to be decidedly dissatisfied. The percentage dissatisfied is simply an expression for the number of "potential complainers".

The dissatisfied are defined as those who vote -2 (cool) or -3 (cold), +2 (warm) or +3(hot) on the 7-point ASHRAE scale as these are considered to be expressions of real discomfort as opposed to those who vote -1 (slightly cool) or +1 (slightly warm). Fanger's study included 1296 subjects similarly clothed (0.6 Clo) and exposed to similar environmental conditions for similar periods of time. The PMV from such a large database was used to derive the percentage dissatisfied which, from the study, was shown to be a function of PMV. Hence the equation for PMV can be used to predict the percentage of persons in a group that will be dissatisfied. This is known as the Predicted Percentage Dissatisfied (PPD). Fanger's study also showed that it is impossible to satisfy all persons in a large group sharing a collective climate. Even with a perfect environmental system, if we could define one as a system that creates absolutely uniform conditions in the occupied zone, one cannot obtain a PPD value lower than 5% for similarly clothed people engaged in similar activity.

Programming the equation for the PPD on a computer allows one to experiment with and quickly calculate or predict the percentage of people who would begin to sense discomfort under conditions obtained by assigning values to these variables. The two personal variables, Clo value and metabolic activity, are within a person's power to change at will. Relative air velocity is one of the environmental variables also included along with the above two as a variable in the computer program. This is because it is relatively easy for a person to vary this factor with a simple ceiling or pedestal fan.

3.3.3 <u>Range of values</u> used:

The following range of values is used as it represents values that we come across in our day to day activity. They are varied one by one in the exercise:

Clo value:	0.25 (very light clothing)	
	0.50 (light summer clothing)	
	0.75 (two layers of light clothing)	
	1.00 (typical business suit)	
Air movement:	0.0-3.0 m/s in increments of 0.5 m/s	
Metabolic activity:	45	kcal/hr (complete rest)
	65	kcal/hr (light work, standing)
	85	kcal/hr (walking)
	130	kcal/hr (house cleaning)

Following Fanger's approach, a temperature is deemed uncomfortable if the PPD for any temperature exceeds one and a half times the minimum PPD. The average minimum PPD is found to be approximately 5.1% (this is based on Fanger's study which found that the minimum PPD will never be less than 5%). One and a half times that is 7.7% and these values are used.

From the permutations carried out with the above values it is found that it is possible to push temperatures accepted as comfortable to a value of up to 31°C (Fig. 14 [each of the curved lines represent the PPD for a combination of Clo value, metabolic rate and air velocity, while the mean radiant temperature and relative humidity are kept constant]). Accepted lower temperatures in the region of 22°C to 25°C have a gradual increase in terms of predicted percentage dissatisfied. The rate of increase of PPD for the higher temperatures, from 28°C to 31°C, is however, very sharp. The PPD at these temperatures is also very sensitive to the slightest changes in the three variables. A point is reached (at 32°C) beyond which even the minimum values for metabolic activity (45 kcal/hr) and Clo value (0.0) combined with an air velocity of 3 m/s will not be able to push the temperature accepted as comfortable further up. The PPD even half a degree Celsius beyond this point is more than 50%. This is because it is now very close to skin temperature.[16]

> *It can be seen that for constant comfort, the mean skin temperature decreases with increasing activity (for metabolic activity at 50 kcal/hr.m², skin temperature is 34°C, for 150 kcal/hr.m², skin temperature is 31°C.*
> (Fanger, 1970)

Although it is seen that the acceptable upper limits for air temperature can be as high as 31°C, the rapid rate of increase of PPD for minute changes of environmental variables precludes it from being used satisfactorily as

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16. Above 33°C, deep body temperature begins to be affected and prolonged exposure to high temperatures will lead to heat stress (Givoni, 1976).

a practically acceptable temperature. Therefore, a lower value, where the rate of increase in PPD is not so rapid, is chosen.

This value is around 28°C[17] and the conditions under which it is found to be an acceptable temperature are :

i) A Clo value of up to 0.75

ii) A metabolic activity up to 65 kcal/hr

iii) Air movement between 1 and 2 m/s.

Considering that Fanger's equation has been incorporated into the ASHRAE standards for human comfort (ASHRAE, 1985), this exercise with the equation for PMV helps base the assumptions for internal temperature settings for calculating cooling energy in the DEROB exercises that follow.

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17. This value corresponds to a field study carried out by the Indian Institute of Science's ASTRA division (Application of Science and Technology to Rural Areas) located in Bangalore. The author came across this at a talk held during a seminar in Bangalore about eight to ten years ago. Attempts to obtain the article via email met with no success.

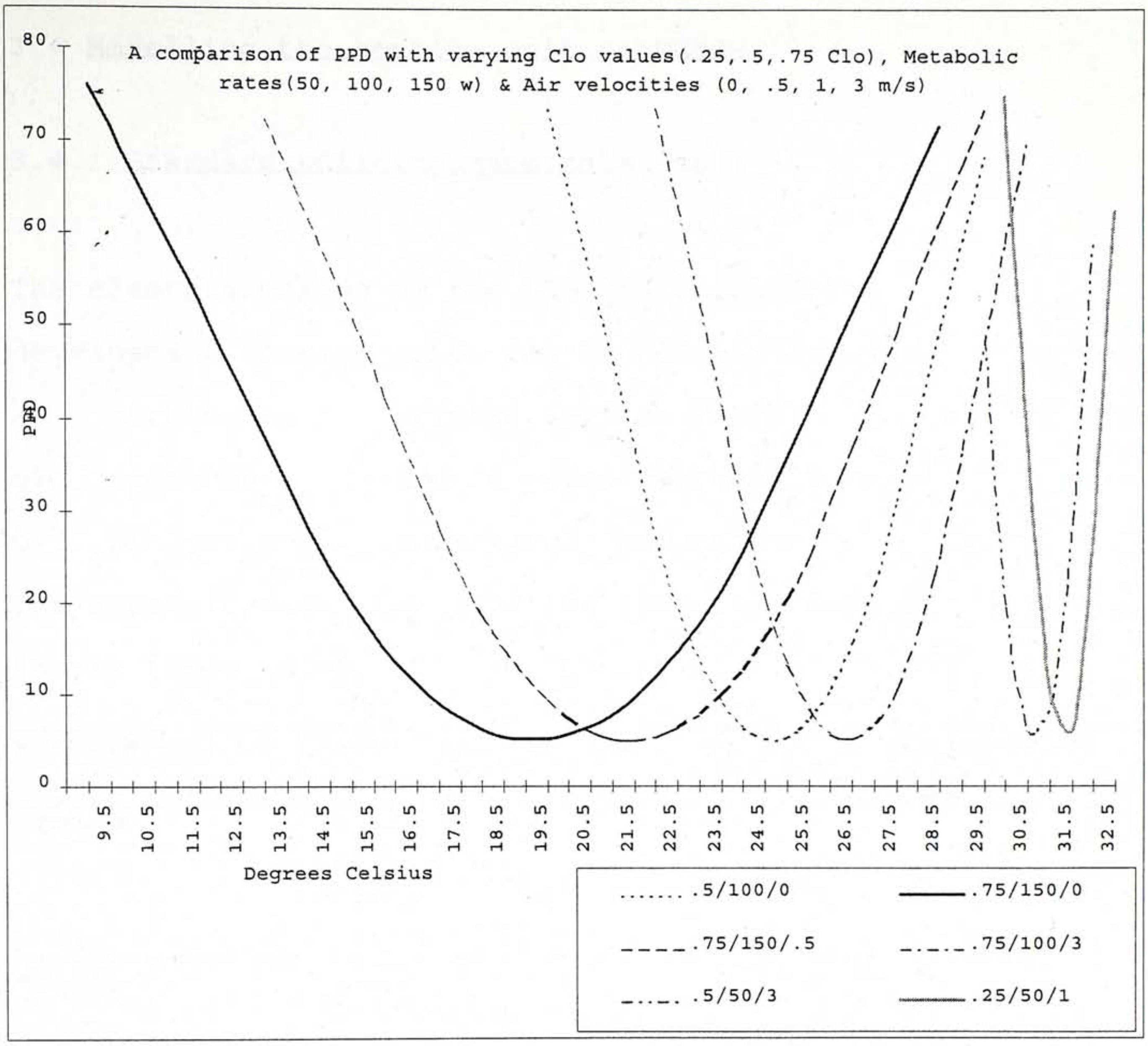

Fig. 14: Variations of PPD

3.4 Modelling the housing unit on DEROB

3.4.1 Standard building materials used:

The elements making up the LIG/MIG incremental development housing units can be classified into:

a) structure (floors, walls, roofs)

b) openings (doors, windows, ventilators)

c) projections (overhangs, balconies)

The standard materials used for these elements are shown in the table below:

Element	Materials commonly used	Thermal performance based on
Floors	Stone, Concrete, Concrete with cement mosaic tiles.	Thickness 100 - 150 mm
Walls	Brick, Soil Cement block, Stone, Concrete block.	Thickness 115 - 460 mm Orientation Color Shading on walls
Horizontal Roofs	Concrete, Clay tiles on concrete purlins.	Thickness 100 -125 mm Water proofing Color Shading on roof
Openings: Windows Doors Ventilators	Wood, Steel.	Sizes Orientation Glazing
Shading components	Concrete, Stone.	Size Direction

The above classification is referred to in the exercises that follow.

3.4.2 Modelling building materials in DEROB.

'MATLIB' (MATerials LIBrary) is a DEROB input file that stores the thermal properties of building materials, which are:

i) conductivity

ii) specific heat

iii) density

iv) radiation

A numeric code is attached to each material. Just the code number for a material need be entered and the program will default to its properties as stored in this file. Apart from storing the properties of common building materials, this also means that fictional materials can be stored just as well in this file. Such fictional material can be assigned properties as desired by the user, such as extremely low conductivity, density or specific heat capacity. These materials can be used in specific walls in a building in order to concentrate the search for results elsewhere. For example, in order to study just the thermal response of a roof to solar radiation, all the other walls[18] defining a room can be forced to be well insulated, and therefore, for the purpose of that study, not participate in the thermal exchange. The roof would now effectively be the only barrier between the exterior and the interior.

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18. In DEROB, all surfaces (walls, roofs, windows, doors, etc.) enclosing a volume are termed as "walls". All volumes (rooms) enclosed within a building are serially numbered from 1 up. The outside of a building is volume 0 and the earth is volume -1.

3.4.3 Development of a method for evaluating thermal performance.

A study was set up within the DEROB framework whereby the various elements in a building were investigated in isolation (as described in section 3.4.2). Investigative studies were initially made of a simple one-room building. It was quickly realised that the advantages or disadvantages of a particular element in a building would have to be stated by unit area or volume in order to be able to easily apply them as design guidelines.

This involved simplifying the building's description to one cube (1m x 1m x 1m)[19] and then:

i) Assuming the cube's location in total shade vs. in sunlight to study the effects of direct solar radiation,

ii) Varying wall & roof thicknesses to study the thermal behavior of wall mass in shade and sunlight,

iii) Varying wall and roof surface colour to study the implication of colour,

iv) Completely rotating the cube in 45° increments to understand the effects of orientation,

19. Cubes of different dimensions ($3m^3$, $5m^3$ and $10m^3$) were also tested and the results reduced accordingly to unit areas and it was found that there was no practical difference in the answers when compared to the results from a cube on 1m.

v) Varying air change capacities and duration to understand the effects of convective heat transfer,

vi) Introducing an internal wall to study the effects of cyclic heat retention and emission by an internal wall mass
and

vii) Introducing shading components over the roof and walls to study the effect of shadow variation.

Thermostat settings were used to *infer* the effects of the above parametric changes by studying the amount of energy required to keep the room at or below the temperature level set. (This temperature, the maximum air temperature acceptable for thermal comfort, was set at 28°C. This was deduced from the previous study conducted using Fanger's comfort equation as well as the recommendation provided by the Indian Institute of Science's ASTRA division.)

The simplified cube was set up in the DIG file which describes building geometry. Standard materials used for floors, walls and roofs were described in the WAL file, which describes wall materials while surface absorptivities and colours were entered in the LUM (luminance tensors) file. Differing orientations and periods of simulation were entered in the SOL (solar penetration) file, while cooling thermostat settings for

28°C and air change rates were controlled in the TL (thermal loads) file[20].

The method of isolating various elements in a building individually and studying their effects upon indoor air temperature is used in the exercises that follow. The evaluations from these studies can be used to draw up design guidelines in the following areas:

i) orientation
ii) walls- thickness/material/color
iii) openings- size & placement
iv) roofs- thickness/material
v) shading components.

20. Dr. Higgs was of the opinion that, to evaluate an element's thermal performance both heating and cooling thermostats were to be maintained at one point, in this case 28°C. This was to determine whether the element in question contributed to raising or lowering cooling or heating loads. But the author felt that heating an element to keep it at 28°C would affect the cooling load required and cooling it would likewise affect the heating load. This aspect was noted, discussed and studied. It was found that maintaining a thermostat set point increased the cooling load by approximately 10%. This aberration was, however, found to be highly consistent. Therefore this consistency itself allows one to accept the aberration - when one considers its convenience as an evaluation method, as the key here lies in observing behavioural trends.

3.4.4. The simplified cube

The simplified cube on 1m. has five of its faces rendered inactive for the purposes of the study. Only one of the faces is considered thermally 'active'. This is achieved as follows:

Enough insulation is placed over the faces required to be inactive. DEROB's remarkable nature with regard to handling the geometry of a 3-dimensional object makes this possible. Walls as described in the geometric descriptions (DIG) file have no thickness while the materials that make up this wall are described, as mentioned earlier, in a separate (WAL) file. This allows for some clever manipulation - any amount of material thickness as described in the WAL file will not alter the basic geometry - i.e., the thickness is neither centred to nor offset inside, or outside, a shape described in the DIG file; just the thermal properties due to this thickness are bestowed upon the wall.[21] (As mentioned in 3.1 earlier, because DEROB reduces a building's description to a R-C network [Resistance-Capacitance electrical network] analogy, the user has to constantly keep switching conventional 3-D thinking 'on' or 'off'.)

From initial studies on the cube it was found that wrapping all the faces of the cube that are required to

21. This was aptly termed *'a geometry in two and a half dimensions'* (during verbal discussions with Dr. Higgs.)

be inactive with about half a metre thickness of white, expanded polystyrene achieves the desired level of inactivity regardless of the surrounding air temperature or amount of direct sunlight falling upon it. Just the active wall under consideration, be it a wall, floor or roof, is given the properties of building materials such as brick, concrete, glass, etc. This is dependent upon the study being undertaken. An interesting concept was *the treatment of air as a building material* that needed to be evaluated for its thermal performance like any other. In a hot dry climate, the benefits of bringing in air that has a temperature lower than the interior are, as shall be seen, measurably beneficial. Consequently, air moving out of a building carries with it heat convected off building elements; in effect the entire outside air is considered a heat sink, provided the outside air is cooler than the indoor air.

4.0 The DEROB EXERCISES

The first part of the investigation involved setting up exercises to study trends in the thermal performance of building elements for the climate in question. Various combinations of materials used were described in the 'WAL' file. Walls, floors and roofs were studied, first to understand their behaviour in this climate and then to observe the trends.

These DEROB exercises are described one by one (sections 4.1 to 4.10) in the following pages. Each exercise has a quest, a description of the setup variation and a finding. The findings are interpreted for arriving at design guidelines.

In order to evaluate the thermal performance realistically, it was recognised that for a pattern of living where people mostly use the roofs of their houses rather than the interior of their houses at night, as much as they do during the day (Fig. 9), thermostat settings did not have to be maintained during those times (from 10 p.m. to 6 a.m.). This was included in the TL file settings during the evaluations. The outdoor temperature during this period is usually close to or below 28°C anyway.

4.1 <u>A study of variations in air changes rates and times</u>

Set up variations:

The first study was set up using the simplified cube placed in regular sunlight. Air infiltration was set to zero but air change rates and durations were varied. The first part of the exercise studied air change durations. This was done to determine the optimum times of day that air changes were required. Air change times and durations can be set in the TL file by setting fan capacities and time intervals for 'on' and 'off' switches (this in effect may also simulate windows that are 'open' or 'closed'). As the outside air temperatures during the day are generally higher than the thermostat set for 28°C, it was required to carefully determine the period when the fans would be 'off' in order not to heat the interior with the hotter convected air brought in from the outside. The second part of the exercise involved varying air change rates. Rates were varied from 0.5 to 32.0 air changes per hour. The air change rates were doubled each time (i.e., 0.5, 1.0, 2.0, 4.0, etc.) and their effects upon the demand for cooling energy were studied. As there is just one thermally active wall with an area of one square metre facing into a volume of one cubic metre, air change 'rates' can also be converted into cubic metres of air required to be exchanged per hour for every square metre of active or external wall.

Findings: -

The results obtained are plotted in graphic format (Figs. 15, 16 & 17) and it is seen that there are durations

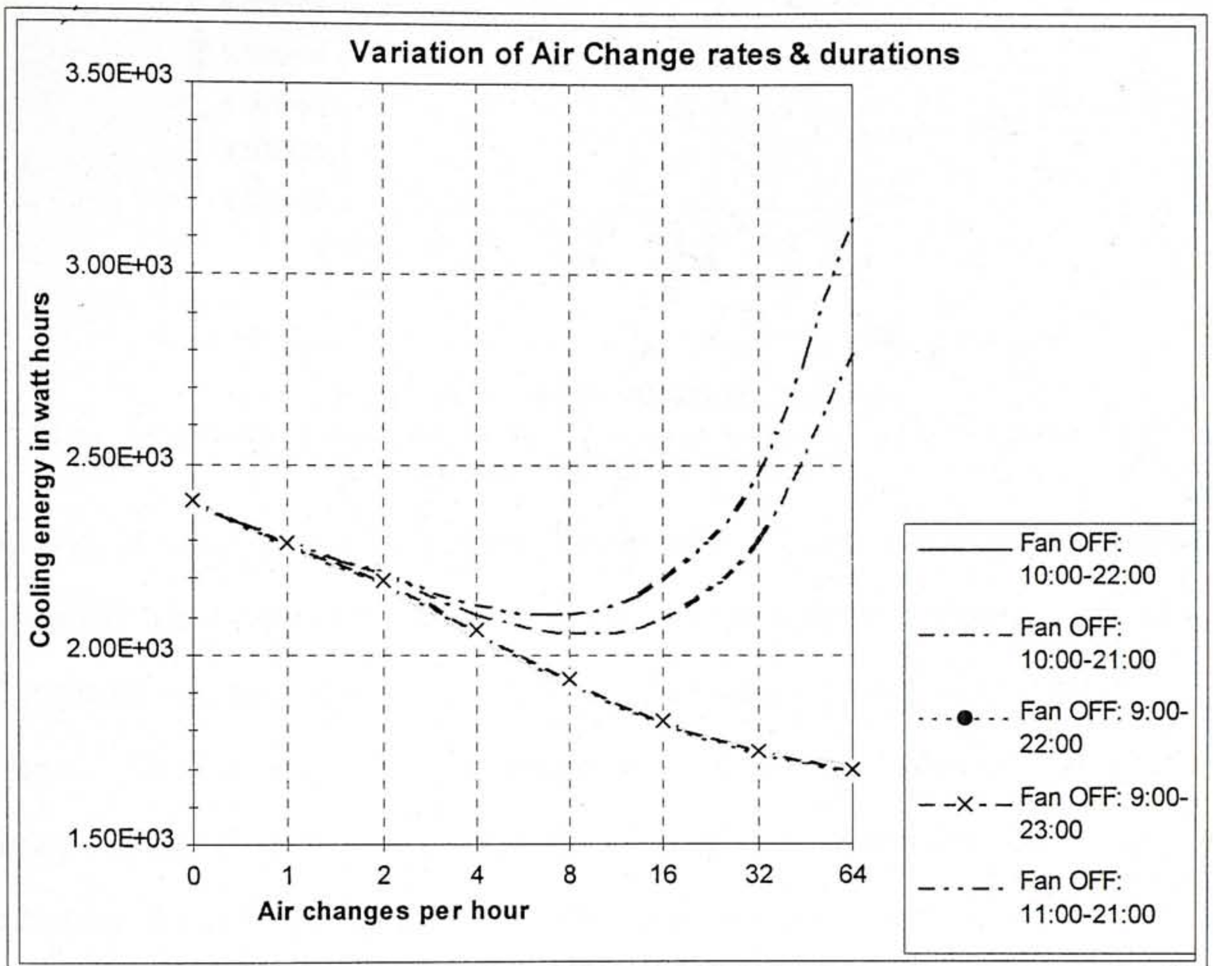

Fig. 15: Effect of varying air change rates and durations
(Graphs for Fan OFF: 9:00-22:00, 10:00-22:00 & 9:00-23:00 are near coincident)

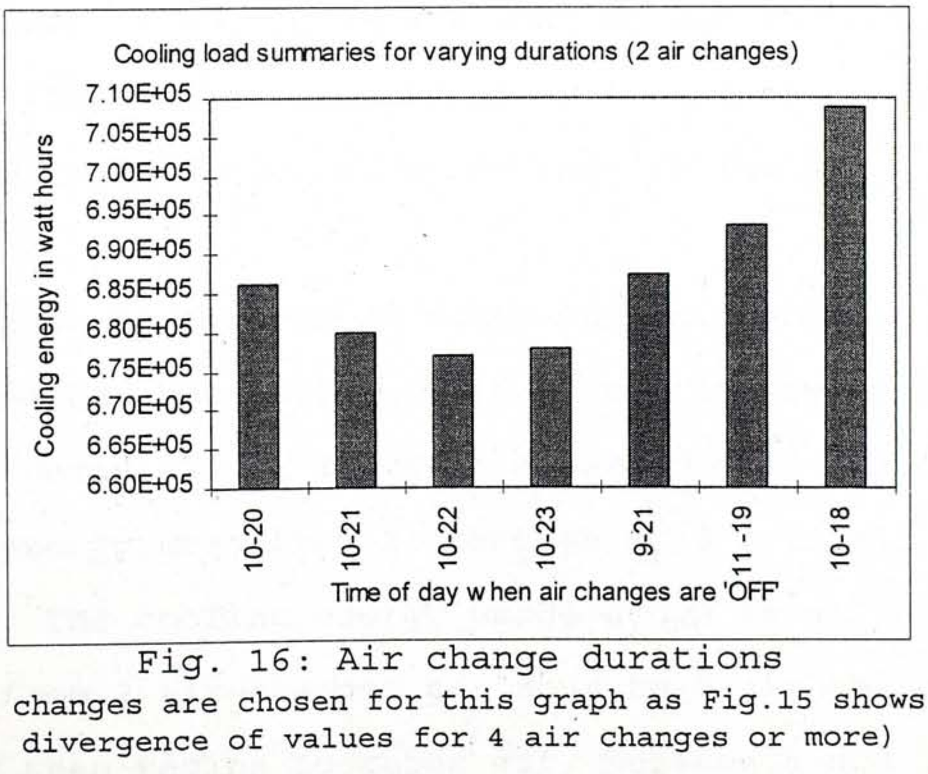

Fig. 16: Air change durations
(2 air changes are chosen for this graph as Fig.15 shows rapid divergence of values for 4 air changes or more)

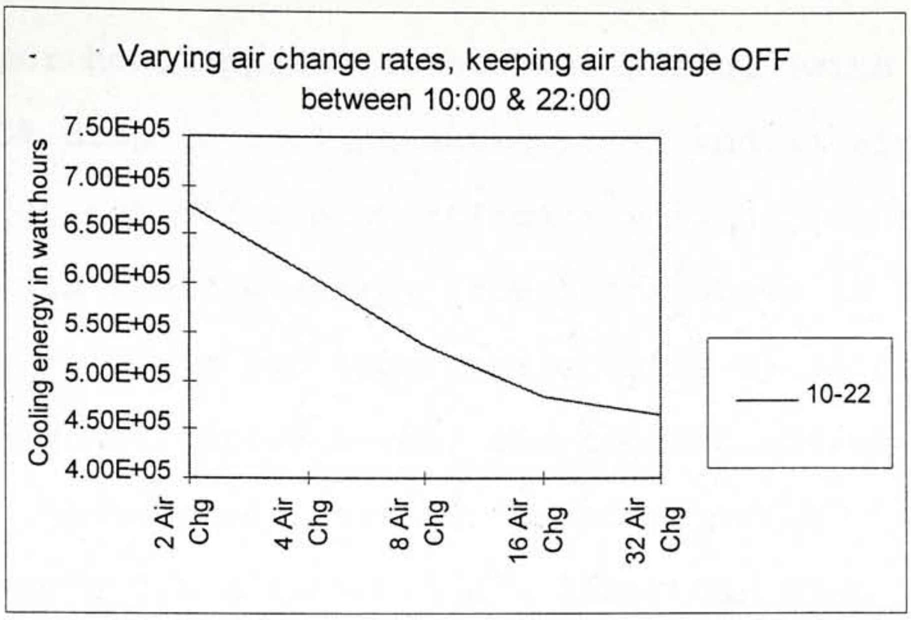

Fig. 17: Air change rates
(Fig. 16 shows that the best time for keeping air changes OFF is between 10:00 - 22:00)

during a day when keeping fans off (i.e. keeping windows closed) is more efficient than others. The most efficient of these times are seen to be between 9:00 and 22:00 hours, 10:00 and 22:00 hours and 9:00 and 23:00 hours. Of these, the practical time for closing windows in the morning is 10:00 hours as we can expect most of the people to have left home by then, while for opening windows at night the practical time is not later than 22:00 hours, as we can expect most people to be back home by then. (Inferences like these will be used to draw up the guidelines in the exercises that follow.)

With respect to air change rates per unit volume, half an air change per hour offers very little improvement in cooling energy usage. There is a marked decrease in cooling energy used from 2, through 4, 8 & 16 air changes per hour. The cooling energy usage drops in a linear fashion from 2 air changes per hour to 8 air changes per hour and then begins to taper off. Between 8 and 16 air changes per hour appears to be most useful (with about a 20% to 25% drop in cooling energy). 32 and 64 air changes per hour do not offer proportionately significant decreases in cooling energy (the graph shown is linear along the 'y' axis but logarithmic [base 2] along the 'x' axis.) In quantitative terms, the cooling energy required for 8 air changes per hour per cubic metre is approximately 0.5 kilowatt-hours less than when there are 0 air changes per hour. (For a room measuring 4m x 3m x 3m, this would translate to an approximate benefit of 18 kilowatt-hours. The energy used by the fans themselves in order to achieve these figures have not been taken into account.)

4.2 The damping effect of the earth's mass below the floor

The damping effect of earth mass below the floor is known to be a useful device to help keep the interior cool (Golany, 1992). The extent of this effect is studied here.

Setup variations:
The exercise was set up in DEROB with the cube placed in regular sunlight. As the effect of the earth's mass below the floor is required to be seen, the floor is considered as having no earth below it in one case, as having earth below it in the other and as insulated in the third case. A preliminary study was done where the three cases were studied in isolation. However, as the floor faces the earth, and all other walls were rendered inactive, there was very little exchange of energy from or to the cube[22]. Therefore, in order to be able to perceive the differences between the above three cases an active wall was introduced. The active wall is a 115 mm brick wall. Infiltration was kept at zero and there were no air changes included.

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22. The following explanation is also quite possible. A surface facing the earth does not receive direct or reflected radiation. Also, the diurnal ranges of soil temperatures are known to be more stable when compared to the diurnal range of air temperatures and are generally quite close to the mean daily temperature (Henderson-Sellers and Robinson, 1986). In this case the mean daily temperature for the hot season was seen to be close to 30°C which is not too far off from the thermostat setting of 28°C inside the cube.

Findings:

The results are studied for the three cases:

i) a floor with no earth below, ii) a floor with earth below and iii) an insulated floor. It is seen from Fig. 18 that there is a considerable drop in cooling energy required to keep the room below 28°C for all orientations of the active wall for cases ii) & iii) when compared with case i), i.e., the earth's mass below the floor is seen to behave as well as the insulated floor. An active wall of 115 mm. is used as the differences show up well with this thickness (a thickness of 115 mm for an east or southeast facing brick wall is not at all efficient as shall be seen in the exercises following this). The cooling effect of the earth's mass upon indoor air temperatures is similar to an insulated floor possibly because we have the cooling thermostat set at 28°C. This may be very close to the temperature of the earth's mass below the floor during the hot period. The important thing to keep in mind, though, is that the earth's mass does not add to the cooling energy requirement. (The diurnal and seasonal variations in temperature within even the first half metre of the earth mass are relatively stable when compared to the steep diurnal and seasonal fluctuations in air temperature[23].)

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23. The practical implementation of this property of the earth's mass is probably with earth sheltered structures. The other immediate suggestion that comes to mind is that houses should, more often than not, be planned for horizontal expansion rather than vertical. This, of course, depends upon the availability of land! (The counter to this suggestion is that the roof area will increase correspondingly - this requires study.)

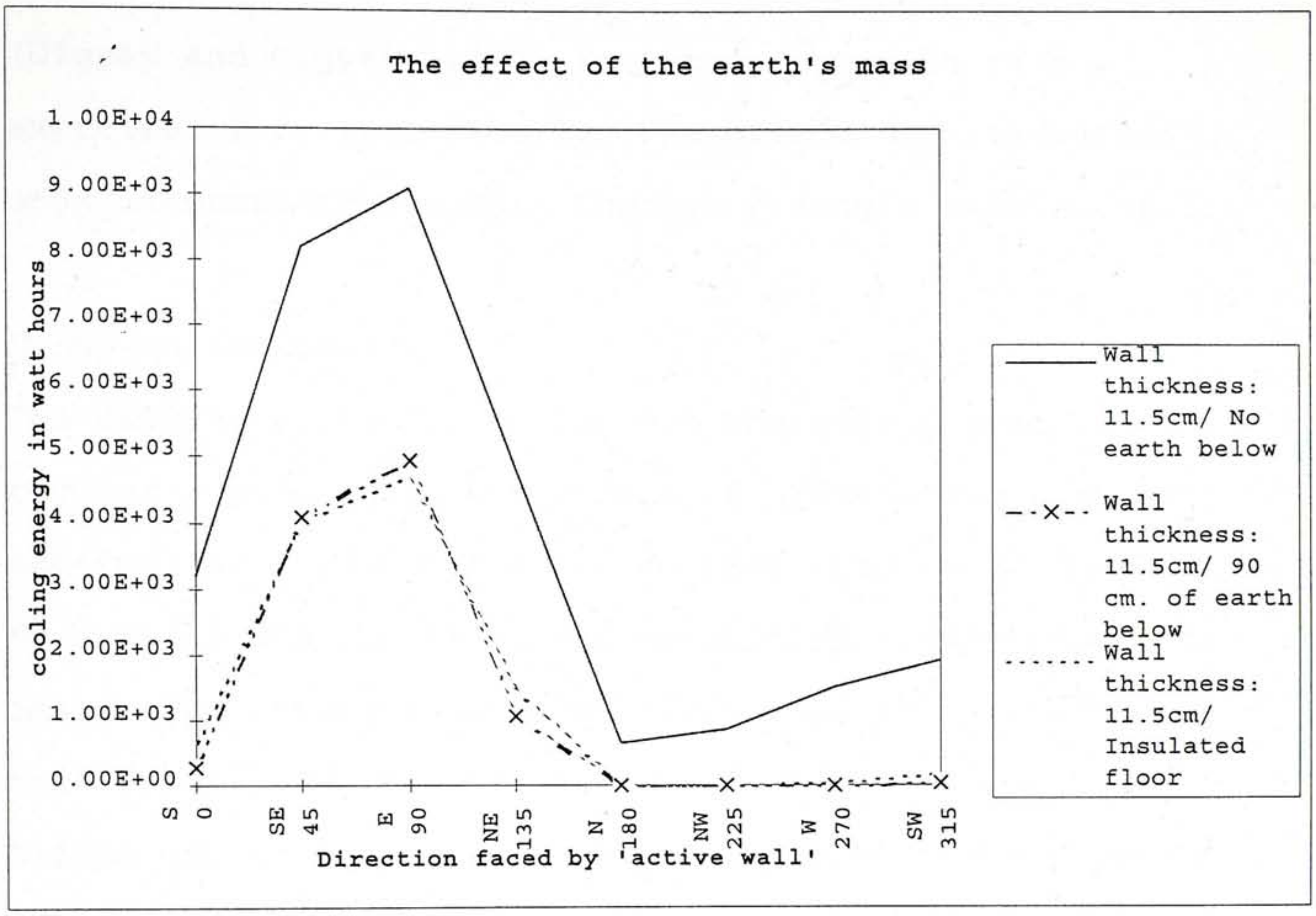


Fig. 18: The damping effect of the earth's mass

4.3 The effect of orientation

The effect of orientation upon internal temperature gains (Olgyay and Olgyay, 1957) is focused upon in this exercise; more specifically, the effect of orientation upon internal temperature through a single exposed wall.

Setup variations:

The DEROB exercise is set up for the cube placed in regular sunlight. As the effect of orientation upon an external wall is required to be seen, the roof, three of four walls and the floor are considered insulated in all cases. The thickness of the fourth wall is varied from a half brick (115 mm) wall to a two brick (460 mm) wall in 115 mm increments. These thicknesses are commonly used for walls. The building is also rotated from 0 to 315 degrees, anticlockwise, at 45 degree intervals. Infiltration is kept at zero and no air changes are included. The cooling thermostat remains set at 28°C.

Findings:

The results are studied for all the four different wall thicknesses, for all eight angles of rotation. It is seen from Fig. 19 that, for every thickness of wall, there is an increase in cooling energy required to keep the room below 28°C as the orientation of the wall approaches east or west.

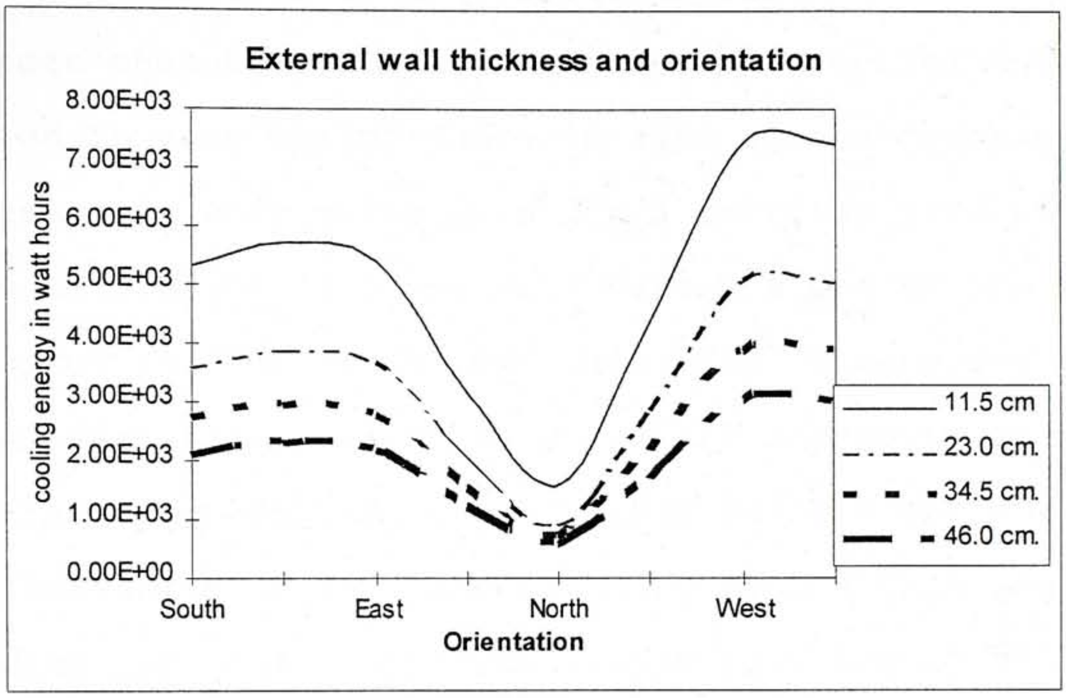


Fig. 19: The effect of orientation upon varying thicknesses

The most energy is required when a wall faces directions between west and southeast, anticlockwise, followed by southeast to east, anticlockwise. (These directions will also be referred to as the 'critical directions'.) It is also seen that the increase in amount of cooling energy required is very sharp. There is also a considerable difference in energy required for a critical direction facing half brick (115 mm) wall versus a one or one and a half brick (230 mm or 345 mm) wall. The morning sun strikes east facing walls with greater intensity than walls facing other directions. These walls store the heat, releasing it into the building with a time lag depending upon their thickness. This time lag coincides with the hottest part of the day for the thinner walls, adding to the discomfort and thus increasing the demand for cooling energy.

The important thing to notice is that, although the differences between the demand for cooling energy required for different wall thicknesses are proportionally similar to each other for all other directions, the actual quantity of cooling energy required is substantially less than that required for the critical directions. This suggests that using heavy brick walls for all non critical directions is not as beneficial as when using it for critical directions. Walls facing non-critical directions consume less than 25% of the cooling energy when compared to the critical directions.

4.4 The effect of external wall mass

The previous exercise studied the effects of orientation upon an external wall mass. It was seen that there were significant differences in cooling energy required when walls were oriented towards the critical directions. In contrast, when walls faced non-critical directions it was seen that there were differences in cooling energy required, but these differences were not as significant. This exercise focuses upon a critical direction and highlights the importance of external wall mass for such orientations.

Setup variations:
The DEROB exercise is set up for the cube placed in regular sunlight. As the effect of the varying of mass of an external wall is required to be seen, the roof, three of four walls and the floor are considered insulated in all cases. The thickness of the fourth wall is varied from a half brick (115 mm) wall to a two brick (460 mm) wall in 115 mm increments. These thicknesses are for commonly used walls. The building was not rotated in this case, as only the critical direction east was studied. Infiltration was kept at zero and there were no air changes included. The cooling thermostat was set to 28°C.

Findings:

The results are studied for all the four different wall thicknesses. It was earlier seen from Fig. 19 that, in every case, there is a drop in cooling energy required to keep the room below 28°C as the thickness of the wall increases. It is also seen from Fig. 20 that the reduction in amount of cooling energy required with increase in wall thickness is not linear - there is a reducing benefit. (The difference, for example, in reduction in cooling energy between an east facing 115 mm wall and a 230 mm wall [twice its thickness] is about 1.7 kWh. The difference between the 115 mm wall and a 345 mm wall [three times its thickness] is about 2.5 kWh. The difference between the 115 mm wall and a 460 mm wall [four times its thickness] is about 3.0 kWh.)

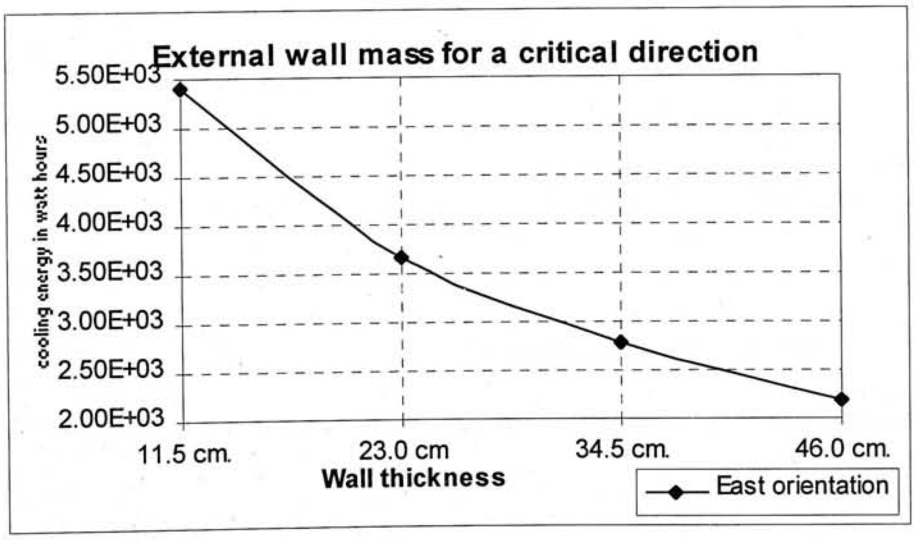


Fig. 20: The effect of external wall mass

4.5 <u>The effect of colour upon external wall mass</u>

The previous exercise focused upon the critical direction east,and highlighted the importance of wall mass for critical directions. This exercise focuses upon colours used on an external wall facing critical directions.

Setup variations:
The DEROB exercise is set up for the cube placed in regular sunlight. As the effect of the varying of colour upon an external wall is required to be seen, the roof, three of four walls and the floor are considered insulated in all cases. The thickness of the fourth wall is kept constant at one brick (230 mm). The building is not rotated in this case, as only the critical direction east is studied. Infiltration is kept at zero and there are no air changes included. The cooling thermostat is set to 28°C. Variation in colour upon a wall is simulated in DEROB by varying the absorptivity of a wall. This is done in the LUM (luminance tensor) file. Very light colours have absorptivities close to 0.1 (white) and very dark colours have absorptivities close to 0.9 (black). These values along with two values in between (0.33 and 0.66) are used to represent a broad range of colour shades.

Findings:

The results are studied for all the four colours. It was earlier seen from Fig. 19 that, in every case, there is a drop in cooling energy required to keep the room below 28°C as the thickness of the external wall increased. It is now seen from Fig. 21 that there is a considerable reduction in amount of cooling energy required with increased lightness of colour upon a wall. (The difference in reduction in cooling energy between an east facing 230 mm wall with an absorptivity of 0.66 and an absorptivity of 0.33 is about 2.2 kWh.) Fig. 21a shows the same data displayed using colour as the basis for comparison. The comparison between varying the thickness of a wall and varying the colour reveals a 'tradeoff', i.e., light colours upon walls are seen to perform as well as thicker walls. An east facing 460 mm thick brick wall having an absorptivity of 0.67 is outperformed by a 230 mm thick brick wall having an absorptivity of 0.33. However as the absorptivities lessen (i.e., as the colour lightens) these tradeoffs narrow.

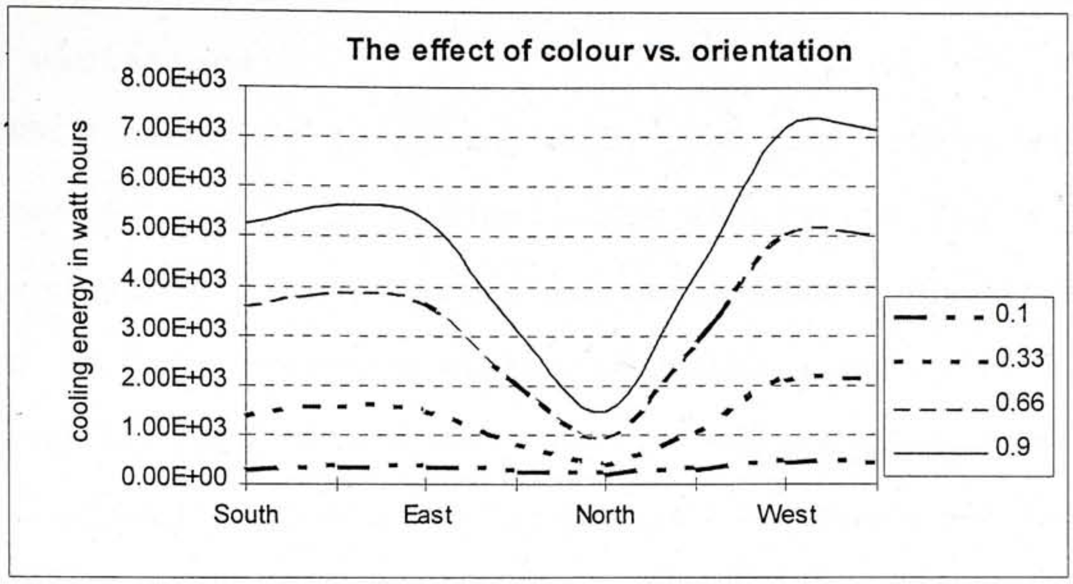


Fig. 21: The effect of colour upon external wall mass

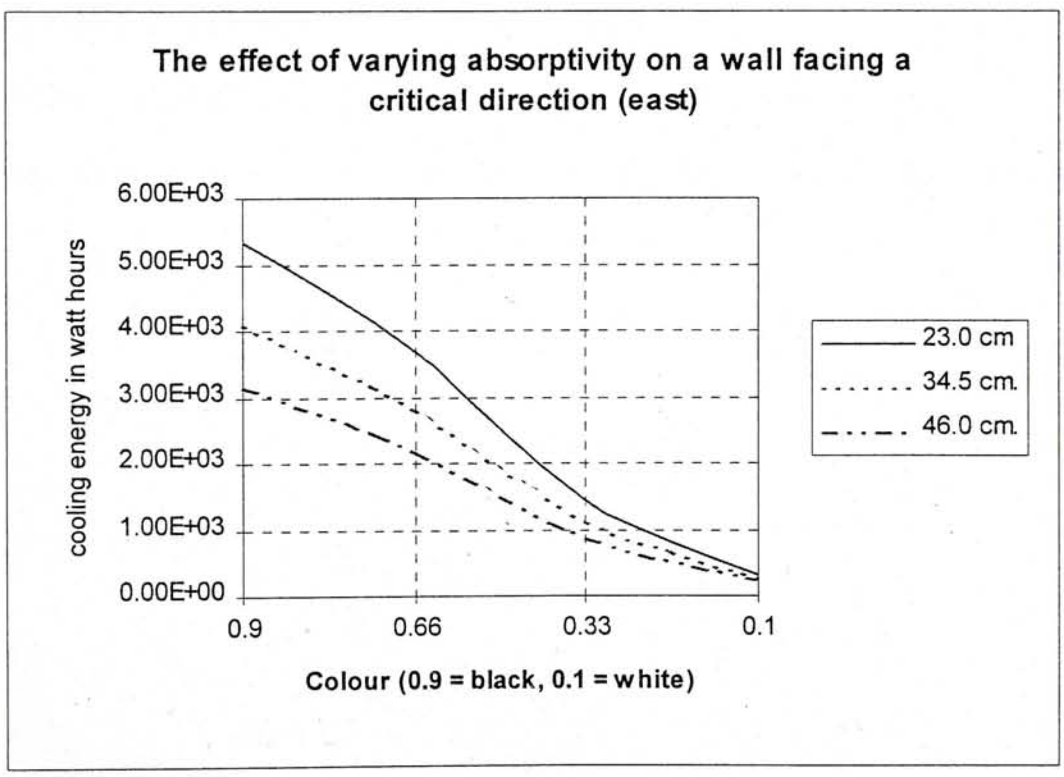
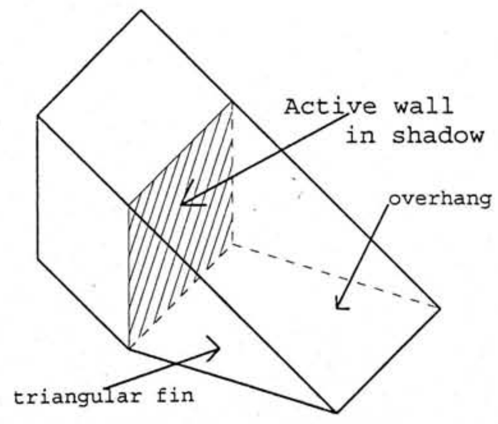


Fig. 21a: A comparison of the effect of reducing the absorptivity vs. increasing the mass of an external wall.

4.6 The effect of shadowing upon a building

Setup variations:

The DEROB exercise is set up such that the active wall of the cube is mostly in shadow. The simulation for a shadowed wall is achieved by adding a simple shading device (a deep overhang with triangular fins) over the wall required to be studied. As the effect of shadowing versus sunlight upon an external wall is required to be seen, the roof, three of four walls and the floor are considered insulated in all cases. The thickness of the fourth wall is varied from a half brick (115 mm) wall to a two brick (460 mm) wall in 115 mm increments. These thicknesses are for commonly used walls. The building is also rotated from 0 to 315 degrees at 45 degree intervals. Infiltration is kept at zero and no air changes are included. The cooling thermostat is set to 28°C.



The shading device over the active wall.

Findings:

Except for approximately an hour after sunrise (07:00 hours for an external wall facing east or southeast) and an hour before sunset (18:00 hours for an external wall facing west or southwest), the shading device allows for no sunlight to fall on the wall. This is confirmed from the output generated by the SOL (solar penetration) run. The SOL output reported here is condensed from the runs for the eight directions. It shows the presence of sunlight upon the active wall (in this exercise it is "WALL 2") for a fraction of the seventh hour of the day when the active wall faces southeast or east and a fraction of the eighteenth hour of the day when the active wall faces southwest or west. This was also tested with the aid of a sundial[24] (refer Appendix C).

24. Sundials are a very useful tool for running a quick check upon a model (Lynch & Hack, 1984). The trigonometric formulas for ascertaining the position of the sun were entered into the spreadsheet EXCEL to arrive at values for the length of the shadow of a vertical peg. This in turn was translated into plotting information for AutoCAD and sundials can now be easily obtained for any latitude. Dr. Higgs' recent refinement of this tool involved writing an algorithm to plot the sundial directly to screen. The screen can then be 'captured' and plotted on a printer.

A condensed report from the SOL runs for the 8 directions:
(The six columns and 4 rows of figures (24 in all) for WALL 2 refer to the 24 hours in a day from first hour to the sixth, seventh hour to the twelfth, and so on. The hours when some sunlight falls on a wall are shown here underlined & in bold)

SOL RUN FOR SOUTH
WALL 2 DOES NOT RECEIVE SUN AT ALL

SOL RUN FOR SOUTHEAST

WALL	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AREA	1.0	**0.1900**	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

SOL RUN FOR EAST

WALL	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AREA	1.0	**0.4927**	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

SOL RUN FOR NORTHEAST
WALL 2 DOES NOT RECEIVE SUN AT ALL

SOL RUN FOR NORTH
WALL 2 DOES NOT RECEIVE SUN AT ALL

SOL RUN FOR NORTHWEST
WALL 2 DOES NOT RECEIVE SUN AT ALL

SOL RUN FOR WEST

WALL	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AREA	1.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	**0.4926**
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

SOL RUN FOR SOUTHWEST

WALL	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AREA	1.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	**0.1902**
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

From the graph in fig. 22 it is immediately seen that the drop in cooling energy for a shaded wall vs. an unshaded wall facing a critical direction like east is very significant (e.g., over 1.5 kWh/sq.m. for a 345 mm wall) when compared to a north facing wall. For a north facing wall the difference in cooling energy is hardly seen. This suggests that shading elements over walls are extremely useful for critical directions but are not required for non-critical directions.

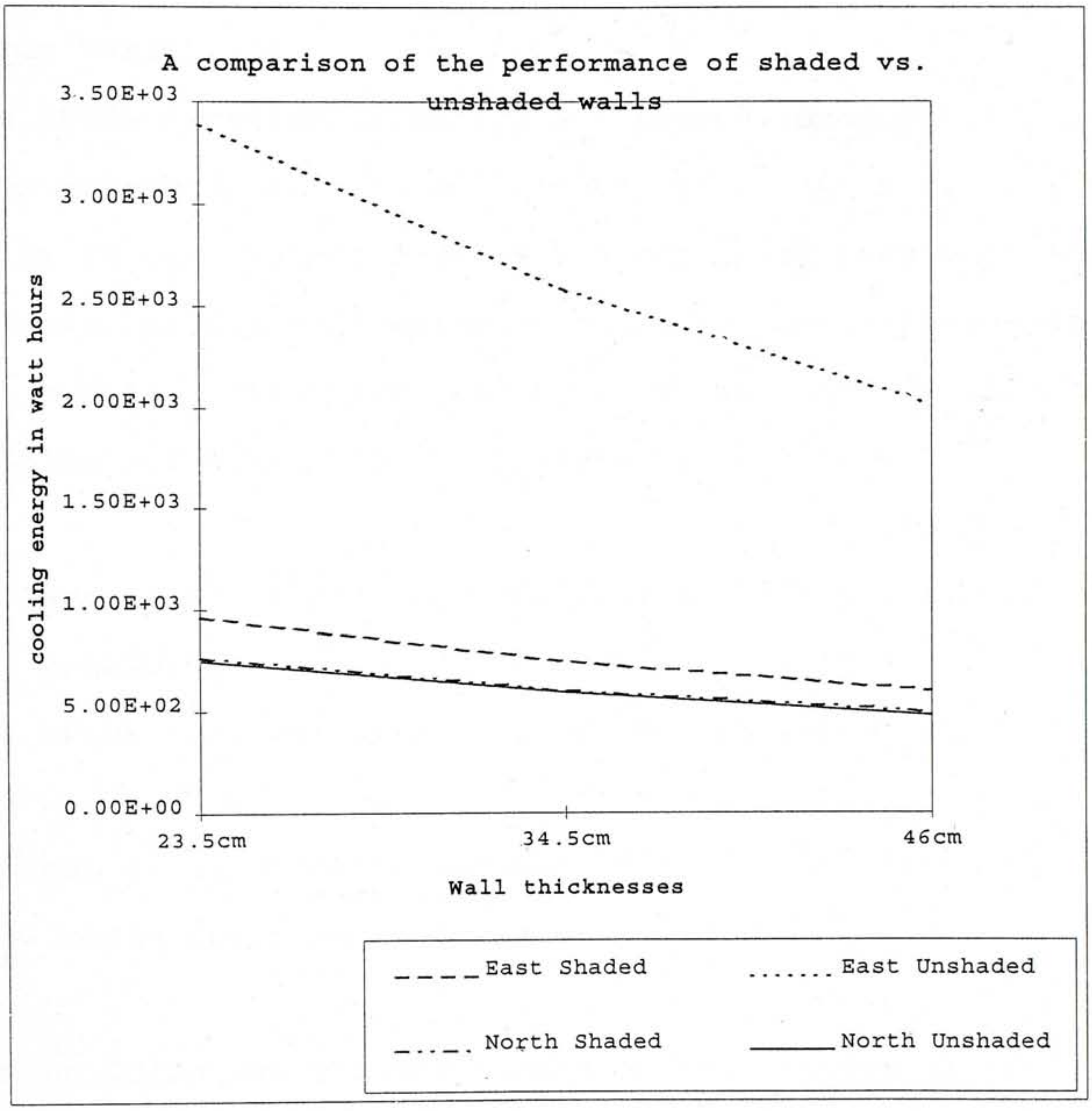


Fig. 22: The effect of shadowing of external walls

4.7 The influence of internal wall mass

The contribution of the thermal mass of an internal wall in keeping indoor temperature stable is studied in this exercise.

Setup variations:
The DEROB exercise is set up for the building placed in regular sunlight, with an internal wall 1.0m x 1.0m, also 0.23m thick. (Again, this is theoretically possible here because DEROB's evaluation of geometric descriptions does not subtract the thickness of walls from the volumes they enclose.) The exercise is divided into two cases.

In case 1, the roof, three of four walls and the floor are considered insulated. The active wall is a either a one brick (230 mm) or a half brick (115 mm) wall.

In case 2, in order to see the effect of the internal wall mass, the inner wall mass is removed.

The building was rotated from 0 to 315 degrees at 45 degree intervals in case 1. Infiltration was kept at zero and there were no air changes included. The cooling thermostat was set to 28°C.

Findings:

The results are studied for both cases with and without the internal wall and for all different angles of rotation. It is seen from Fig. 23 that, for both thicknesses of external wall with the internal wall mass in place, there is a drop in cooling energy required to keep the room below 28 degrees Celsius . The difference in cooling energy required is more obvious, however, when the external wall is thinner, at 115 mm.

A quarter of a cubic meter of internal brick wall mass within a 1 cubic meter volume shows up to half a kilowatt reduction (or a 10% percent reduction) in the cooling energy required to keep the internal temperature at 28°C. This is an average percentage figure for all the directions for the hot period and exhibits the influence of indoor mass as a modulator of the diurnal heat cycle.

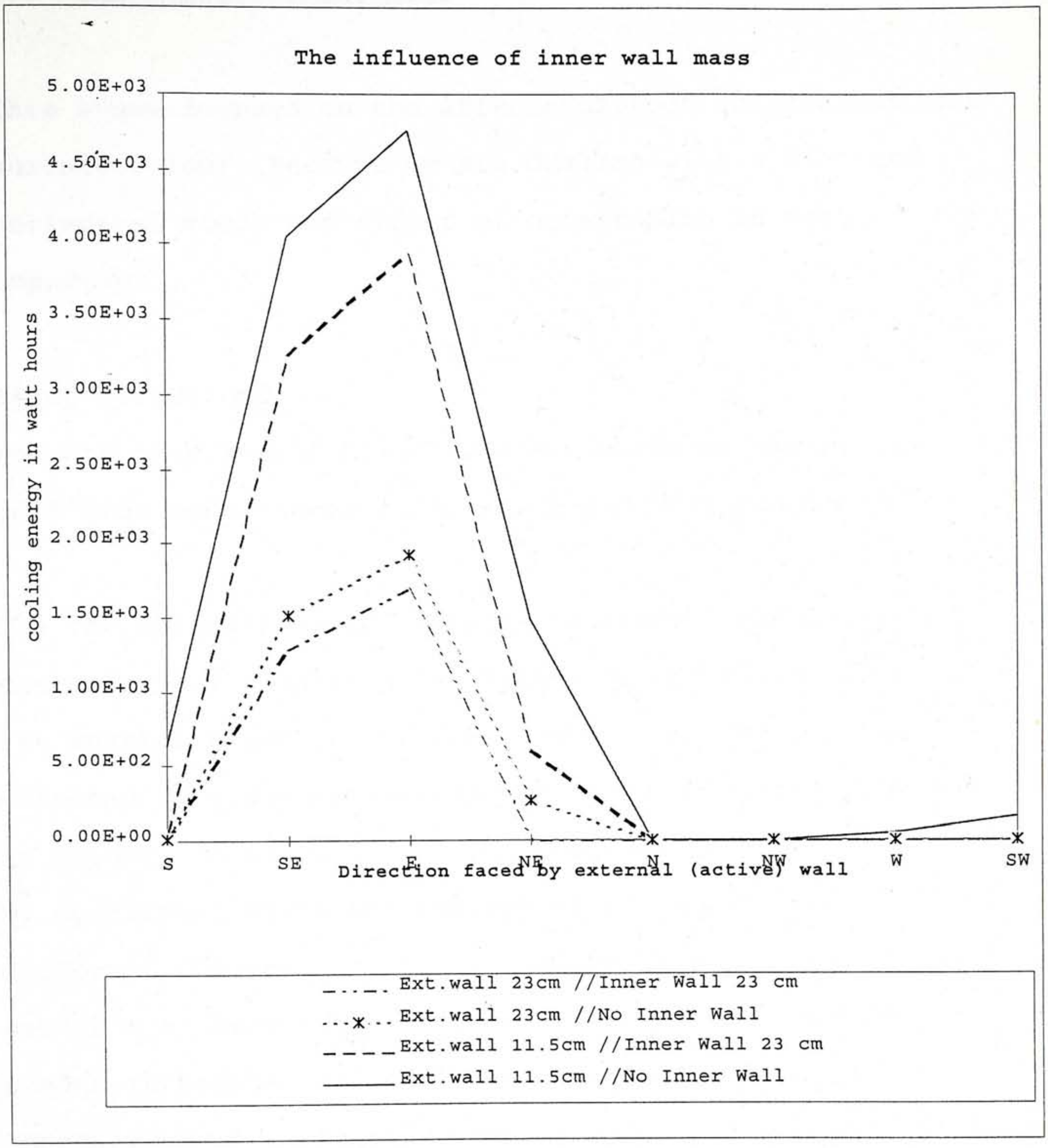


Fig. 23: The influence of internal wall mass

4.8 The effect of the roof

This study focuses on the effects of roof thicknesses and surface colour. Because we are dealing with a flat and horizontal roof, the effect of orientation is not important.

Setup variations:
For the purposes of this study all surfaces except the roof were modelled as if in shade and well insulated.

The variations included changes in the thickness of the concrete roof coupled with changes to the thickness of the weather proof course (WPC)[25] above it. The changes effected by these variations were studied against changes in colour. Colour changes were modelled in the LUM file by specifying different absorptivity figures for different colours. Very dark colours have absorptivities set at 0.9; very light colours are set at 0.1 and the shades in between are set at 0.3, 0.5, 0.6 and 0.7. Thicknesses of roofs used were i) 100 mm of concrete with 125 mm of WPC and ii) 125 mm of concrete with 150 mm of WPC. These thicknesses are taken from standard roof

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25. Weather proof courses (or WPC) on flat roofs are generally made of brick bats in lime or cement mortar. To achieve effective rainwater drainage, the top surface is sloped at not less than 1:60 ("an inch every five feet" rule of thumb). The minimum thickness at the roof edges are usually around 100 to 120 mm. Depending upon the location of rainwater pipes, the WPC may be as thick as 180 to 200 mm at points farthest from the rainwater outlet. WPC is also colloquially known as "surkhi".

thicknesses used in construction in these regions for roof spans not exceeding 3.6 m.

Findings:

From the graph (Fig. 24) it is seen that there is a marked drop in the demand for cooling energy when roof colours are lightened from 0.9 through 0.7, 0.6, 0.5 and 0.3 to 0.1 - the drop each time is very significant and draws attention to the fact that the midday sun can be very effectively dealt with using light or very light colours. The drop in cooling energy loads is considerable - from approximately 8.0 kWh from very dark colour (0.9) roofs to 1.0 kWh for very light colour (0.1) roofs.

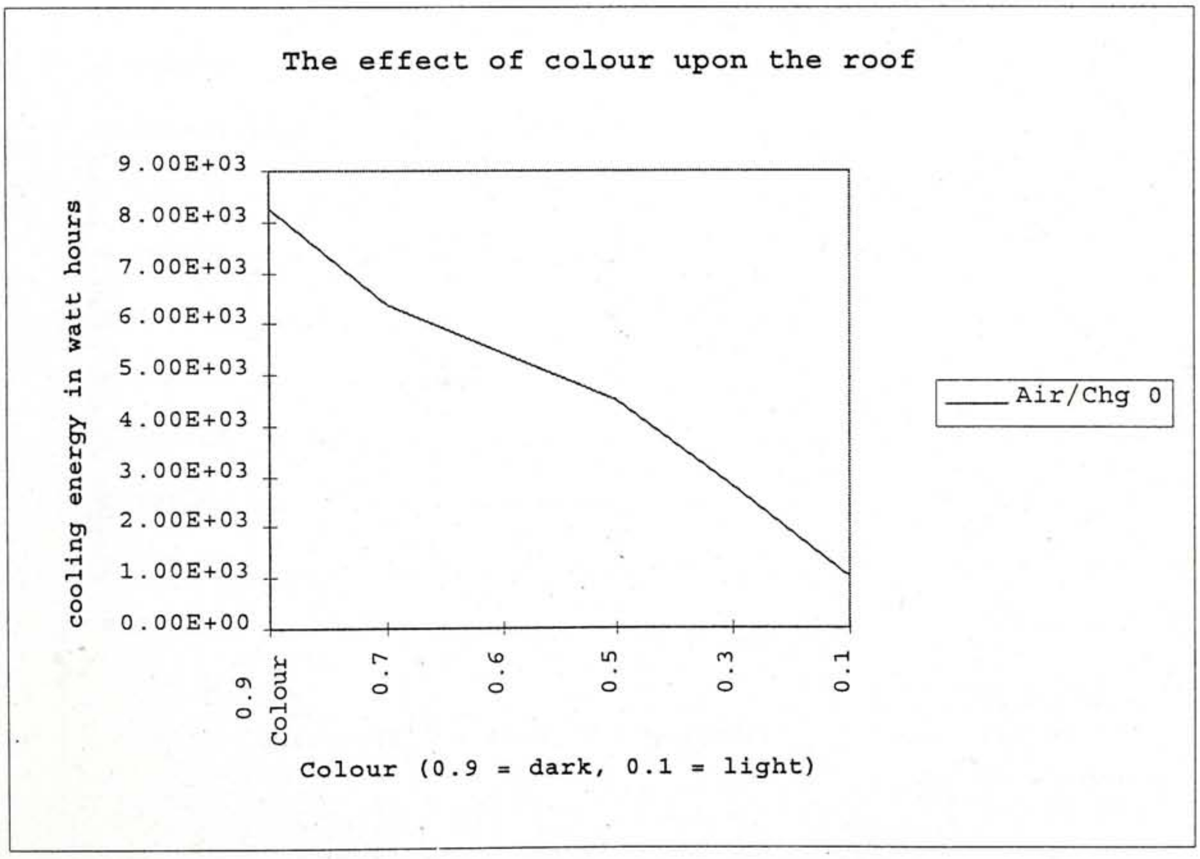

Fig. 24: The effect of variations in colour upon the roof

A comparison of the effectiveness of using light colours over increasing thicknesses for roofs has been made (Fig. 25) and it can be seen that increasing the thickness of the roof by 50 mm (an increase of over 20%) is far less effective than reducing its absorptivity by 20%. For a roof thickness T, where T = 100 mm concrete + 125 mm WPC and an absorptivity equal to 0.6, the cooling energy load is approximately 5.3 kWh. Changing the thickness to 125 mm concrete + 150 mm WPC but keeping the same colour reduces the cooling energy load to 5.0 kWh. However, changing the colour to 0.5 reduces the cooling energy to 4.5 kWh.

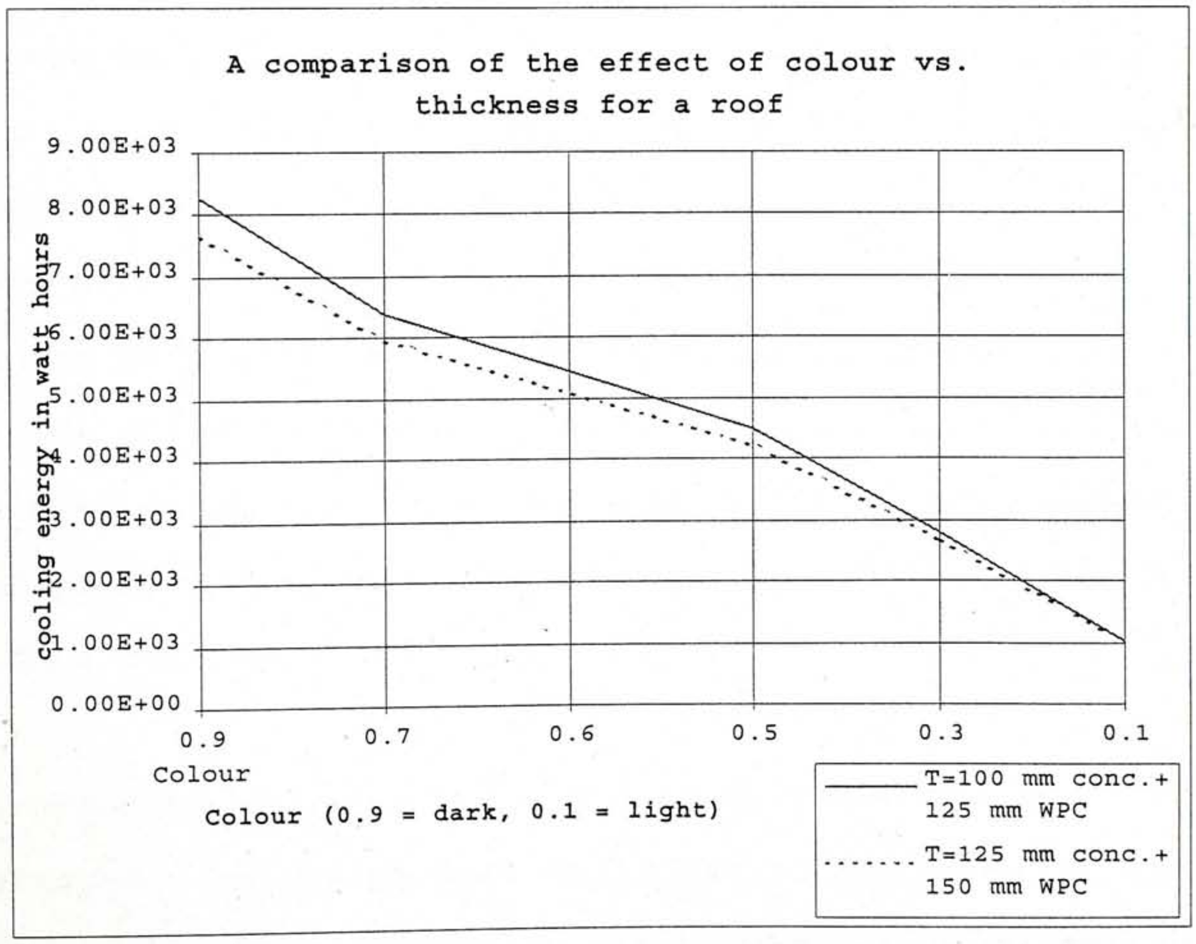

Fig. 25: A comparison of the effect of colour vs. thickness for a roof

4.9 An analysis of parapet walls

When flat roofs are made accessible they are protected at the perimeter by parapet walls. These parapet walls are generally 0.8 to 1.0 meter high and provide varying degrees of shade to the roof depending upon the time of day. This study investigates their effect upon the roof they surround.

Setup variations:
In DEROB any external element not enclosing a volume is treated as a shading element only and does not participate in thermal exchange with the volume proper. In the absence of any parapet wall, all of the roof would see the sky in both the solar and the IR bands. In the presence of a parapet wall as just a shading wall only that part of the roof not in its shadow would see the sky in the solar band and all of the roof would still see all of the sky in the IR band. In DEROB, this situation would be treated as one where there is no interaction between the parapet wall and the roof surface closest to it, say within a meter.

In order to overcome this, the space above the roof surrounded by the parapet walls has to be converted into a 'volume'. This is done by creating a fictional surface made of highly transparent, transmissive glass laid on top of the parapet walls. Introducing the fictional roof will allow this interaction to take place. It will force

DEROB to perform a luminance tensor radiation analysis for the parapet walls in consideration. At the same time in order that this enclosed volume approximate an open one, ventilation rates have to mimic the amount of air that moves across the roof[26].

As the effect of partial shadowing of the roof by the parapet walls needed to be studied, the roof area was split up into perimeter and central zones (Fig. 26). This is because when a surface is partially shaded in DEROB, the amount of insolation received by part of the surface is averaged out over the entire surface and the value is then applied to the surface node for that hour.

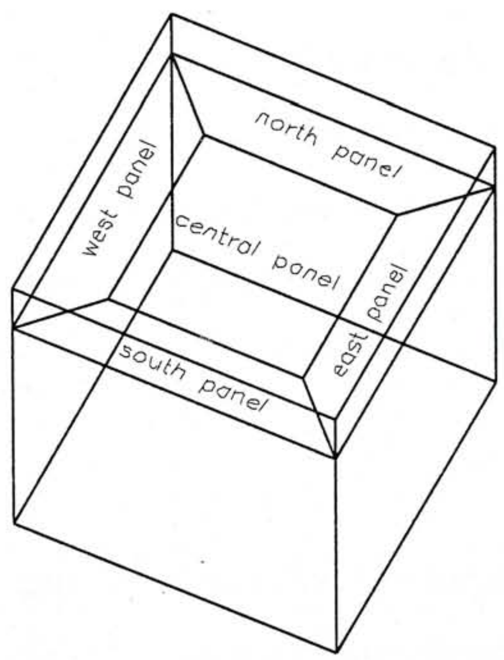

Fig. 26: Roof studies

26. Having a glass roof also meant that the space below it would heat up to unreasonable levels. So the temperature was 'conditioned' every hour to match the outdoor air temperature (the cooling energy required to do this is ignored for the purposed of this study).

To achieve a better feel for the way a flat roof behaves over a day (when parts of the roof are in shade due to the parapet walls) the roof is geometrically described as many adjacent, but smaller, coplanar roofs. This allows for the deployment of as many surface nodes as there are roof parts.

The floor and walls of this room were considered well insulated. The roof alone consisted of real world material - '*surkhi*' waterproofing[27] over a reinforced concrete slab. The perimeter of this roof was bounded by the equivalent of a 0.8 metre high plastered brick parapet wall. The fictional roof for this volume consisted of 99.98 percent transmissive, very thin glass. Now that the parapet walls were made part of a volume, variations in colour upon the surfaces facing the roof as well as the roof itself could be made in the LUM file. Two absorptivities were used, 0.1 for white and 0.9 for black.

Findings:
The effect of the parapet wall's presence can be gauged by comparing the cooling energy required within the volume with those from the previous exercise where only the roof was studied (Fig. 26a). The surface temperature of the roof was also monitored and the fluctuations in temperature of the roof closer to the perimeter were seen

27. Surkhi - colloq., a layer of brick bats in lime mortar laid to a minimum slope of 1:60.

to be more than at the centre. The contrasts offered by near vertical insolation versus shadow at the perimeter are higher. For this latitude and season, the northern panel receives more sunlight than shadow than any other panel and reaches temperatures close to 80°C between 14:00 and 15:00 hours which is about 8°C higher than any other panel.

Variations in colour upon the surfaces of the parapet wall facing the roof did have noticeable effects, with very dark colours performing better than very light colours. Dark colours upon parapet walls helped lower surface temperatures upon the roof. This is due to the fact that light colours reflect radiation better. Being so close to the roof, much of this reflected radiation's first target is the roof. The difference in surface temperatures just due to the colour of the parapet wall is seen to be as much as 10°C for eastern and western panels and about 5°C for northern and southern panels, while the central panel is hardly affected[28].

There is also a drop in cooling energy used within the cube by around 11% - from 12.5 kWh to 11.0 kWh - when dark colours are used on the insides of the parapet wall.

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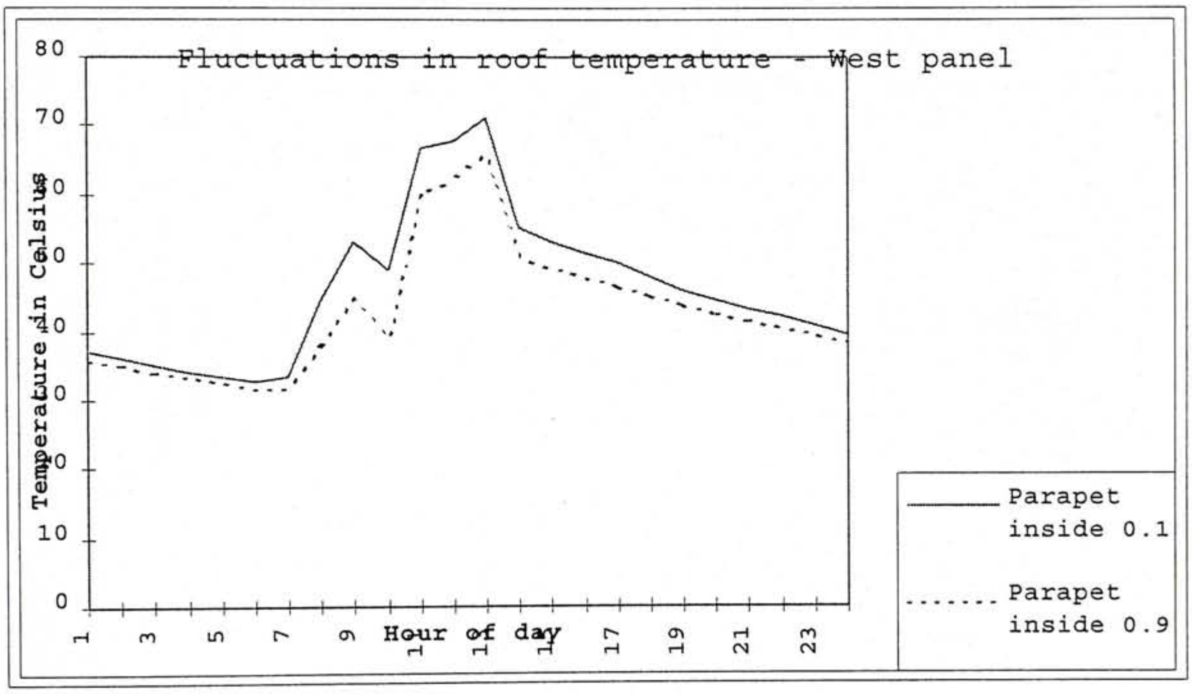
28. A perusal of the geometric shape factors explains this: for the dimensions used, the shape factor between the central panel and any parapet wall is close to 0, while the shape factor between a panel at the perimeter and the parapet wall adjacent to it is close to 0.5.

The conjecture now is that if higher parapet walls are used to enhance shading upon the roof, as in a courtyard, then the contribution of dark colours upon the surfaces facing the roof may be proportionately better. This aspect has not been studied in detail and requires more study. (For example, it may be in conflict with the performance requirements of the courtyard wall if it encloses a room on the other side.)



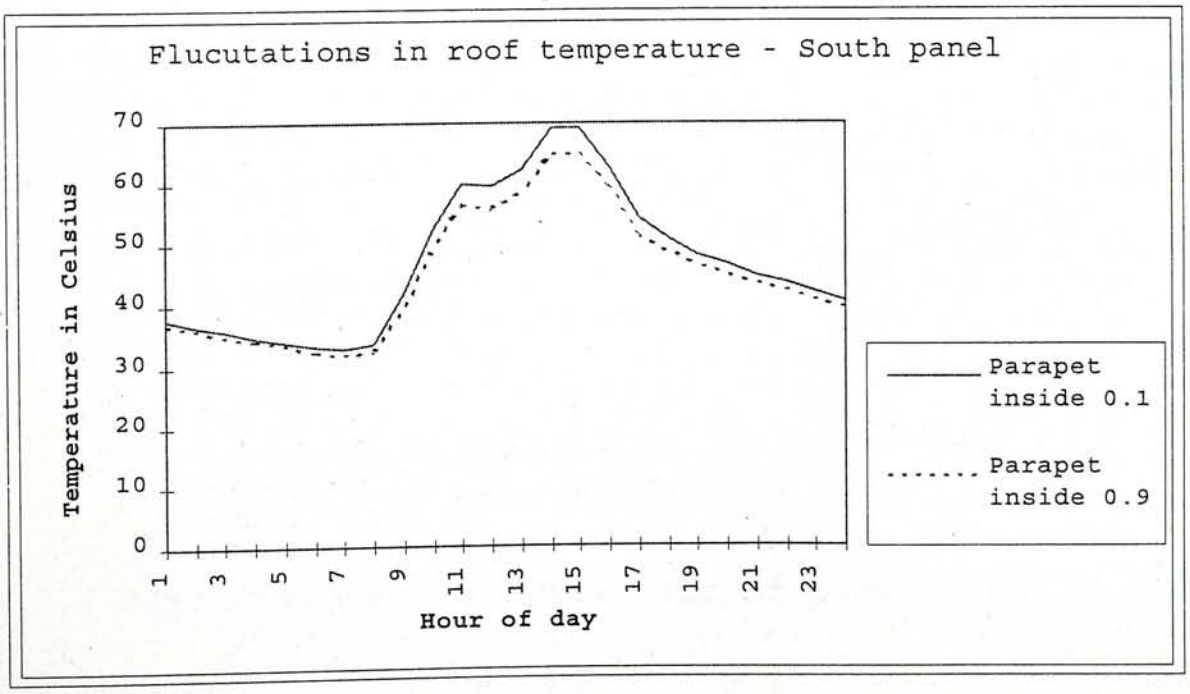
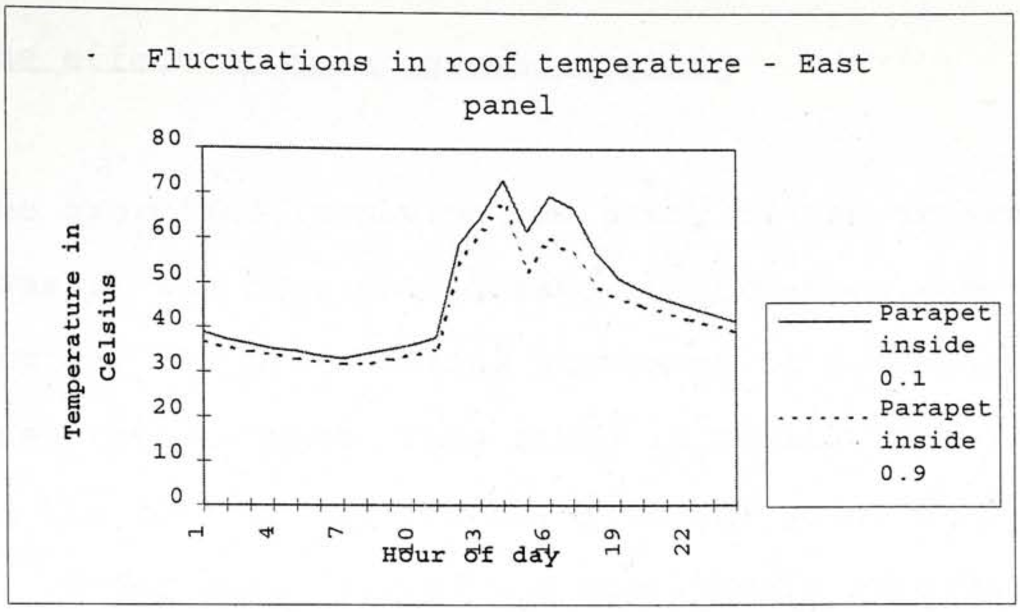
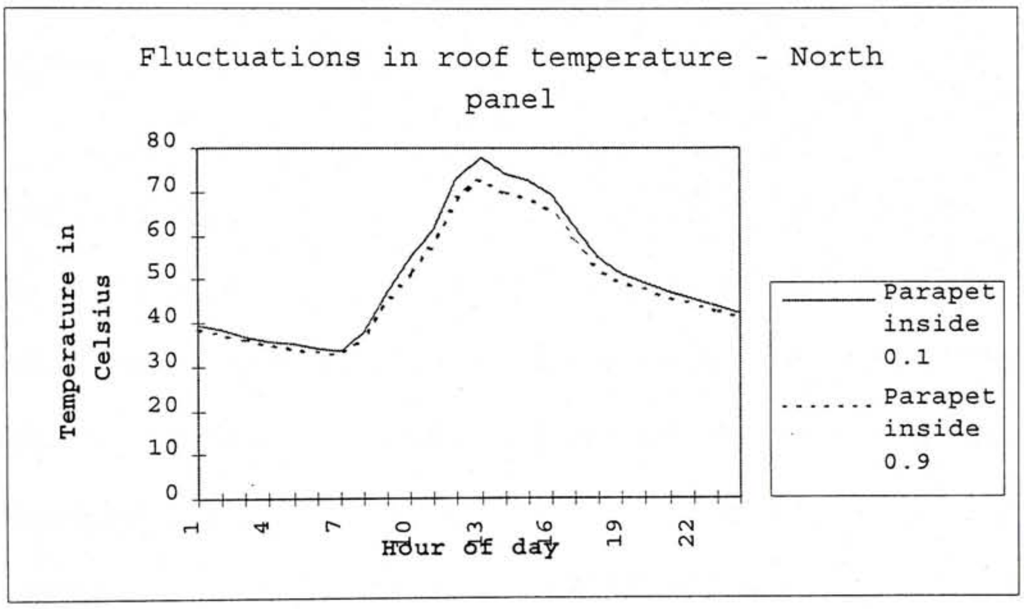


Fig. 26a: Analysis of parapet walls





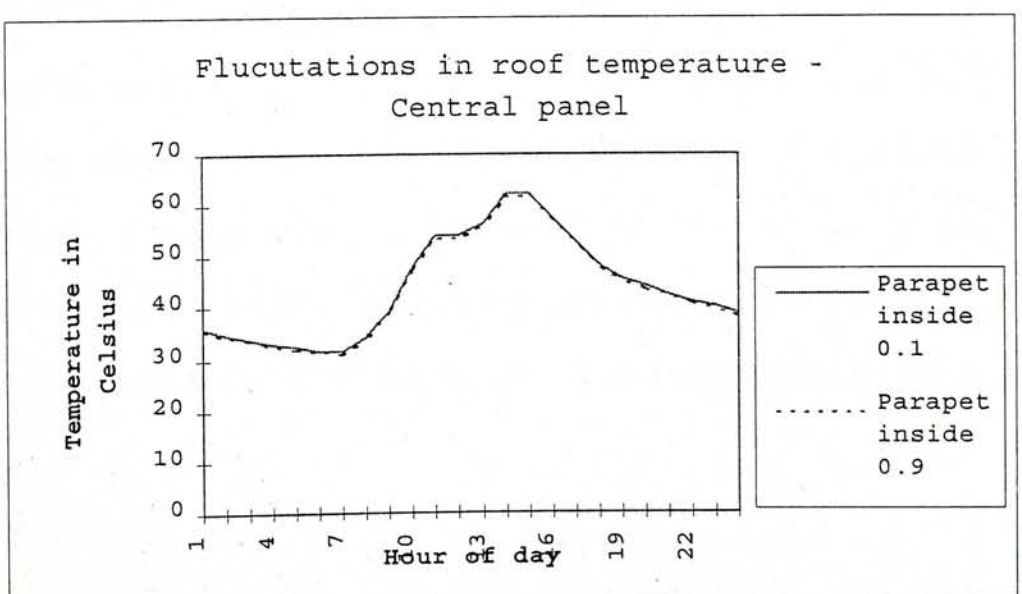


Fig. 26a: (contd.) Analysis of parapet walls

4.10 The effect of openings and shading

From the exercises involving the study of the external wall mass it was seen that greater thicknesses were required for the orientations southeast to northeast and southwest to northwest. This study is similarly aimed at finding the optimum directions, from the point of view of thermal performance, for having openings in external walls and the shading required over them to exclude direct gain.

Setup variations:
The cube is placed in sunlight with the active wall made of glass. There are four variations to the cube. The first one includes no shading protection for the glass wall (window). A shading device is introduced in the other three in the form of an overhang and two triangular fins on either side (fig. 27). The ratio of the overhang's projection to the height of the window is varied in three steps - 1:3 [shallow], 2:3 [moderate] and 1:1 [deep] (these represent shading for solar altitudes of 72°, 56° and 45°). The cube is rotated through all the eight orientations for each of the four variations.

Findings:
From the graph in Fig. 27a it is seen that the directions from northwest to southwest are responsible for the

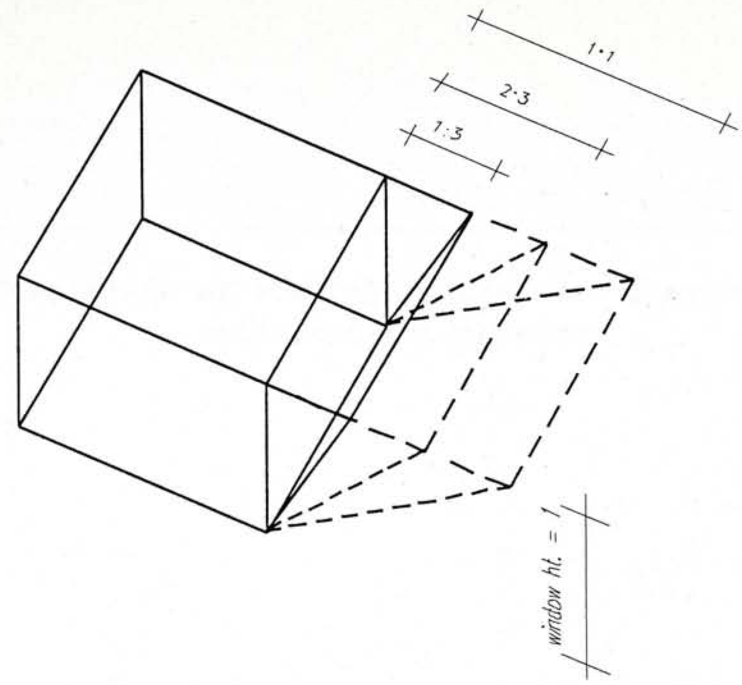


Fig. 27: Shading device ratios

highest cooling energy consumption (over 6 kWh), followed by the directions from southeast and east (around 5 kWh) when no shading device is used. Even when just a shallow shading device (1:3) is used the cooling energy drops dramatically and, surprisingly uniformly, by nearly 3 kWh for all the directions. The moderate to deep shading devices (2:3 and 1:1) do offer some benefits, but the drop in cooling energy are not as dramatic. It is also seen that, apart from west, the cooling energy used evens out for all other directions to about 2 kWh when a deep shading device (1:1) is used.

The ideal orientations, using just shallow shading devices (1:3), appear to be north, northeast and south (i.e., one can have 1.5 m high windows in these orientations and have just 0.5 m deep shading devices).

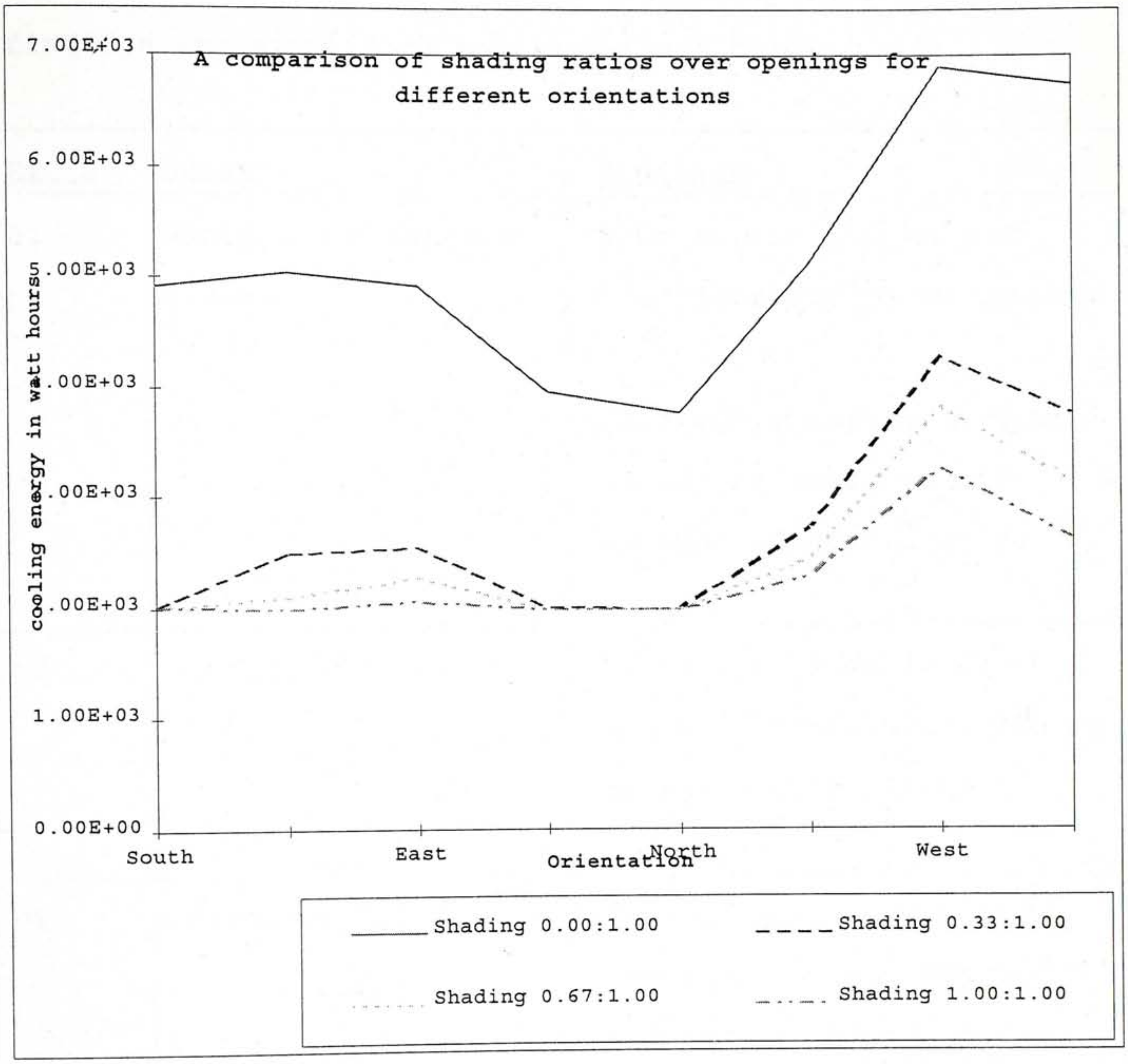


Fig. 27a: The effect of openings and shading

5.0 A SUMMARY OF RESULTS

Each of the exercises had a quest and a finding. The findings are simplified and summarized below:

Ex. #	Quest	Findings
01	Ventilation rates & times	*8 to 16 air changes per hour is found to be optimum *This air change mechanism should be switched off between 10:00 and 21:00 hours.
02	Damping effect of the floor	*Earth's mass below floor on grade is beneficial; floors do not require insulating material.
03	Effect of Orientation	*Facades from southeast to northeast, anticlockwise, and west to southwest are the 'critical directions'.
04	Shading of walls	*Very effective, especially on facades facing the critical directions.

05	External wall mass	*Diminishing returns with increase in thickness. *Consider one and a half to two brick thick walls only for facades facing critical directions. *Half brick thick walls are acceptable for all non-critical orientations. *External walls facing critical directions have to be painted white for maximum performance. A white-washed one brick thick wall *will* perform better than a dark (absorptivity > 0.7) two brick thick wall.
06	Internal wall mass ('wall' also refers to floors of the upper floors, if any) - see footnote no.18.	*It is useful to have internal mass. It does not, however, play a critical role in the thermal performance of a building.

07	Roof	*Existing thicknesses used seem to be adequate *but* *white colour upon the roof dramatically improves its thermal performance.
08	Parapet walls	*Higher parapet walls increase shadowing on the roof and hence improve roof performance. *If the surfaces of the parapet walls are painted black, the surface temperatures of roofs can be lowered by about 10°C.
09	Openings & shading	*Ideal orientations are north, northeast and south with shallow shading devices and *southeast, east and northwest with moderate shading.

5.0.1 A summary brief:

The following brief is written looking back at the objectives highlighted in section 2.0 and reading the summary in section 5.0 (many of the findings are, not surprisingly, confirmations of commonly known design guidelines):

i) Orientation: Critical orientations are southeast to northeast and southwest to northwest, anticlockwise.

ii) Walls: Thicker walls are required for external walls facing critical orientations. Light colours on external surfaces improve the their thermal performance.

iii) Roofs: From the point of view of thermal performance, the colour of the roof is extremely critical. It is more important to have light coloured roofs than increase its thickness.

iv) Openings and shading components: Ideal orientations are northeast to north, anticlockwise, and south. Shading required is minimal. For directions southeast to east, anticlockwise, and northwest, moderate shading is required.

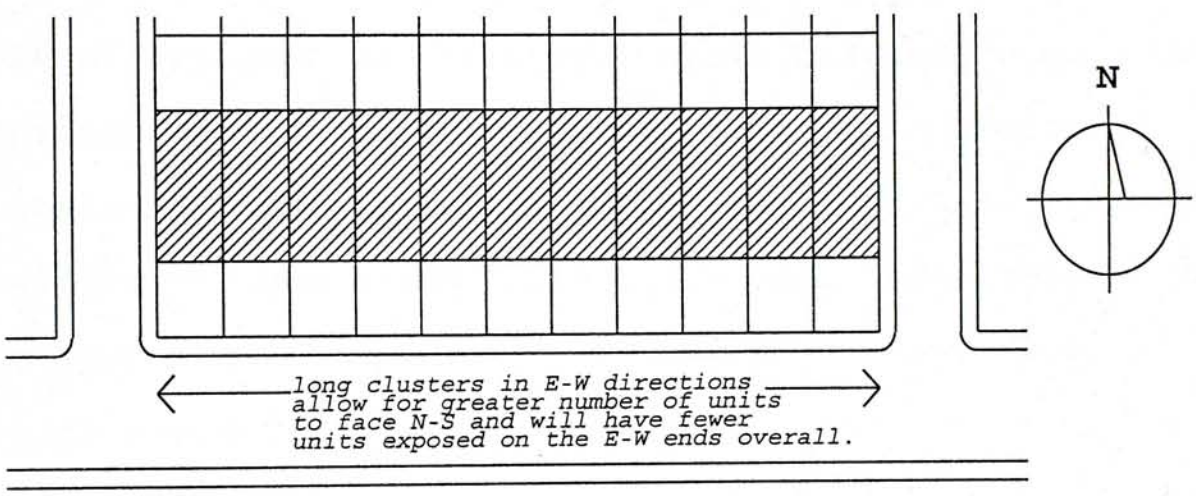
Apart from these, the other important area covered in the investigation was the study of air change rates and durations.

5.1 Preliminary Design Guidelines

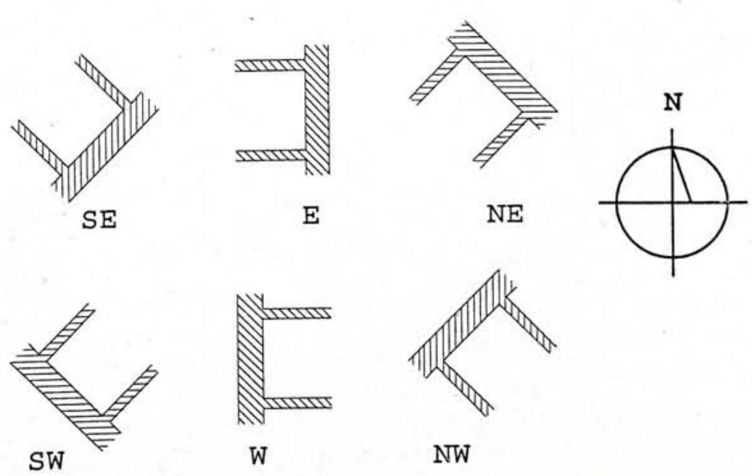
The various exercises conducted allow one to compare and contrast accepted construction methods and patterns of usage. The evaluations help in increasing, to some extent, the understanding of these issues. This increased awareness helps in proposing changes and modifications to a certain degree. It is however, relatively easier to propose a modification to a construction method than to dictate a change of pattern of use.

Also, the evaluation method used here should be noted with care. The simulations consisted of a housing unit simplified to a single cube. Hypothetical exercises were then performed upon it using 'synthetic' weather. Although all this was done systematically and logically, it still means that findings from the results will tend to be suggestive rather than conclusive. Clearly, much more work needs to be done in this field. More building materials and construction practices need to be studied. Future studies comparing simulations with data recorded on site are required. Pending which, the findings from the exercises allow for the suggestion of some architectural design guidelines for the climate in question. These preliminary guidelines are to be viewed in the light of thermal performance. They are:

1) At site planning stage, one of the major decisions involves orientation: it would be ideal to see that as few units as possible face east-west. Also, row housing clusters with units facing north-south should have few end units exposed directly to these directions, i.e., longer the cluster, smaller the number of end units.

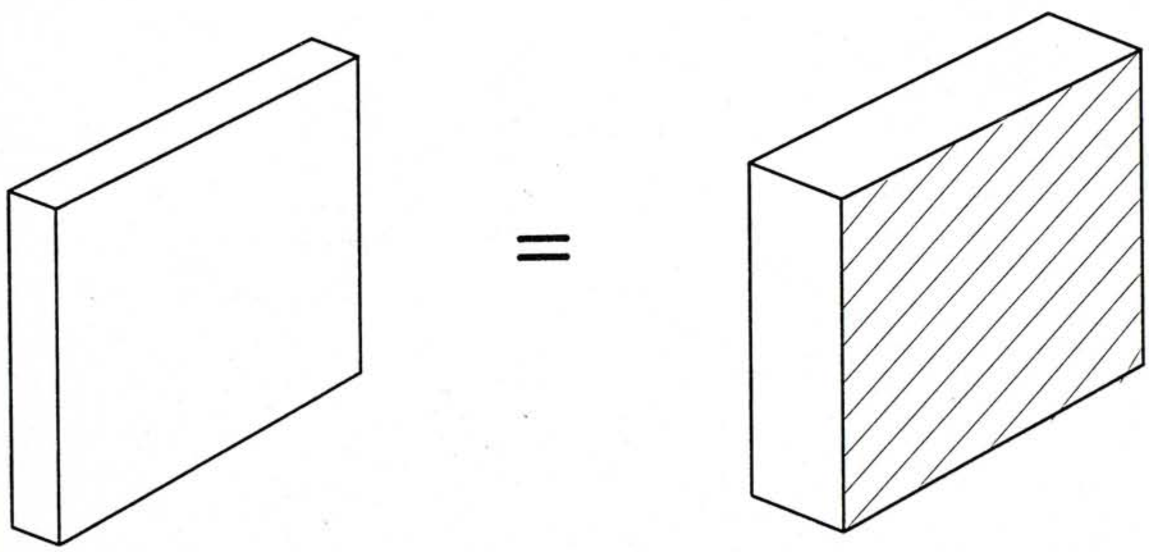


2) One and a half brick thick walls are necessary for external walls facing the critical directions between southeast to northeast and northwest to southwest, anticlockwise. If economics permit, two brick thick walls for these directions are recommended.



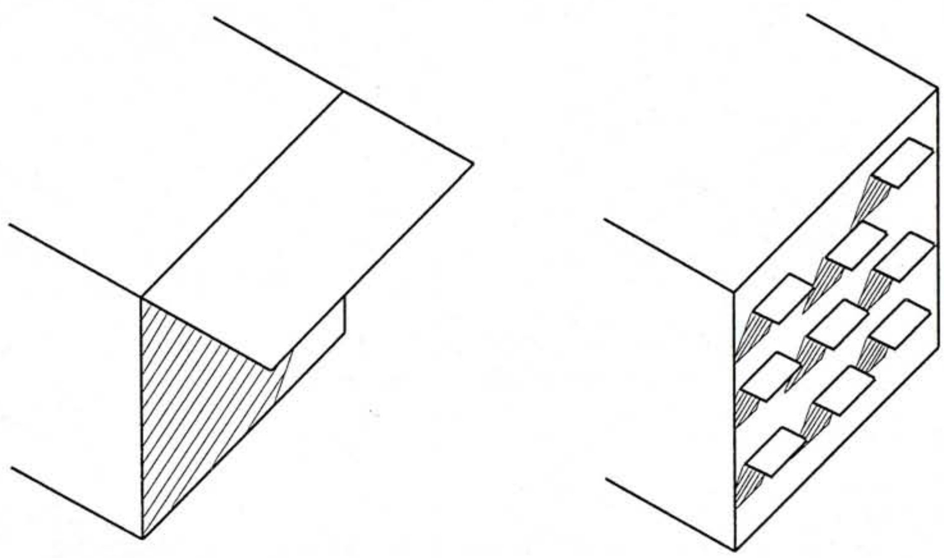
3) All other external walls, common walls between units and all internal load bearing walls need not be more than one brick thick. This, of course, may have to be viewed more carefully in the light of structural requirement and acoustic privacy.

4) The external surface of external walls facing the critical directions from southeast to northeast and from southwest to northwest, anticlockwise, should be painted white to reduce absorptivity. A one brick thick wall painted white (absorptivity < 0.33) is more efficient than a two brick thick wall that is dark in colour (absorptivity > 0.66). This is very important with respect to structural economy.



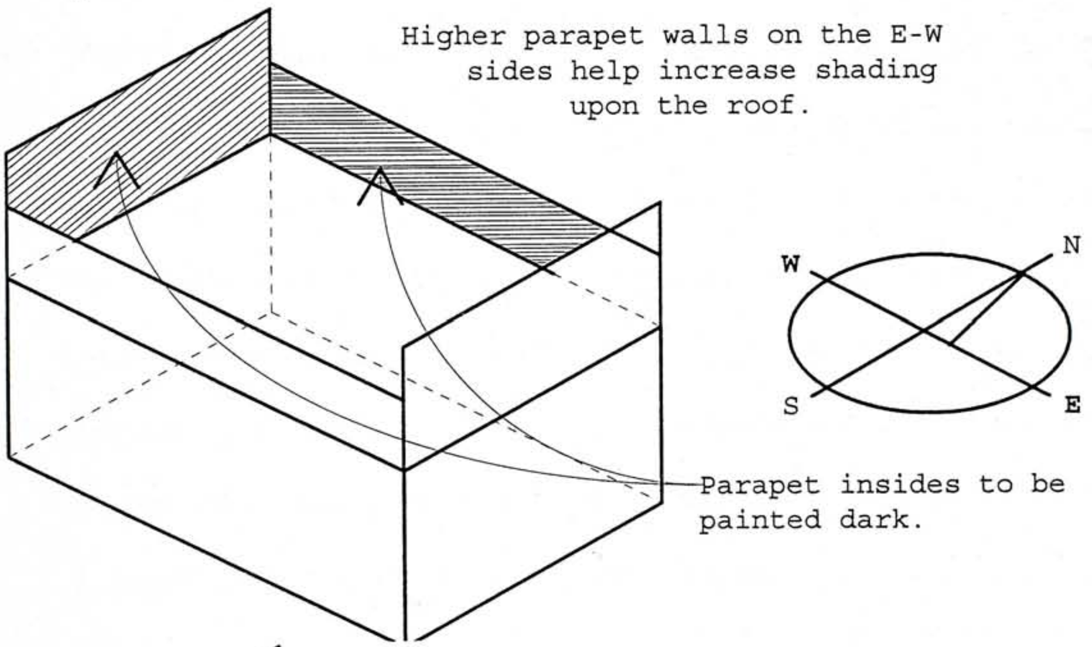
Thin, light coloured wall = Thick, dark coloured wall

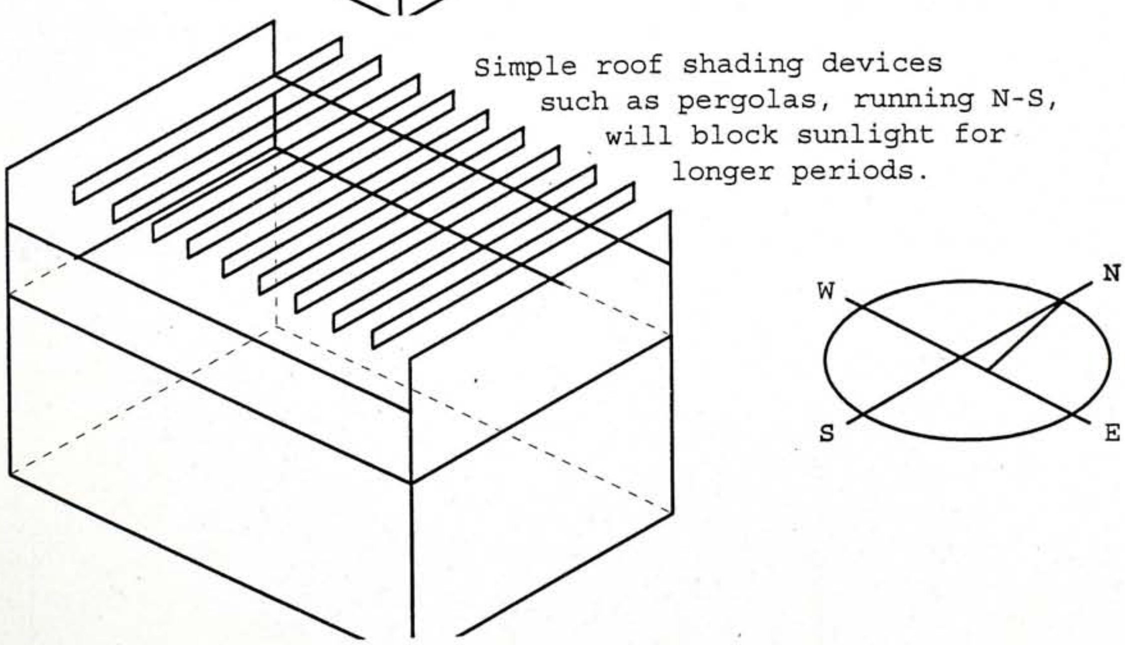
5) Shading components in the form of overhangs over walls facing the critical directions from southeast to northeast and from northwest to southwest, anticlockwise, improve the thermal performance of the unit. As it would take a large overhang to shade such walls (due to their very orientation), one of the methods suggested is to embed small, projecting stone slabs in the wall[29]. The number of slabs and the distance they project will vary with their size and spacing. Considerable shading upon walls can be achieved.



29. Horizontal projections only have been mentioned here as it is a simple matter to introduce a stone slab in place of a few bricks in any given course. The introduction of vertical shading devices, however, in a wall is rather more complicated. The brick course has to stop and start, while bonding has to be accounted for in every alternate course.

6) With respect to parapet walls, higher the eastern & western parapet walls, greater the duration of shadowing upon the roof. However, as no amount of increase in height will help shade the roof towards midday and early afternoon, simple roof shading devices (such as pergolas) are also strongly recommended. (The performance of pergolas have not been investigated in this study. It is mentioned here only to imply the importance of shading the roof.) The surfaces of parapet walls facing the roof should be painted black.

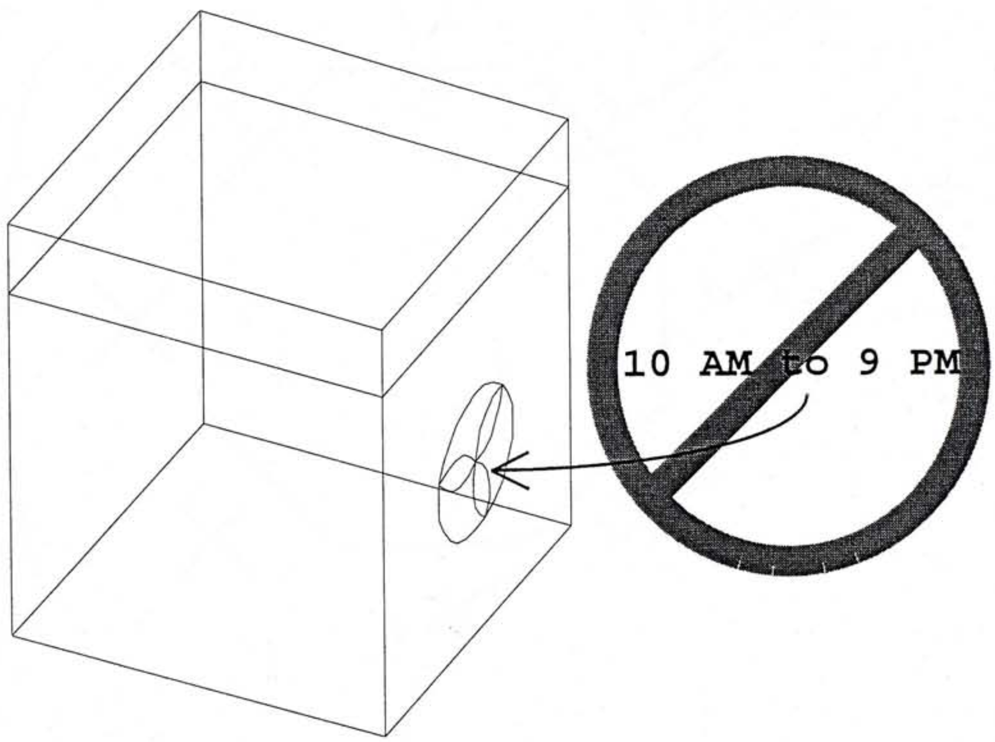




7) While the thicknesses of roofs used seem to be adequate, the introduction of very light colours for the roof will drastically improve the thermal performance of the roof. Just one coat of whitewash prior to the onset of the hot season is required (this is proposed as a cost conscious solution and will not stay long on the surface if people still need to use the roof. Longer lasting solutions will require costlier treatment either by using white paints or by laying white tiles.)

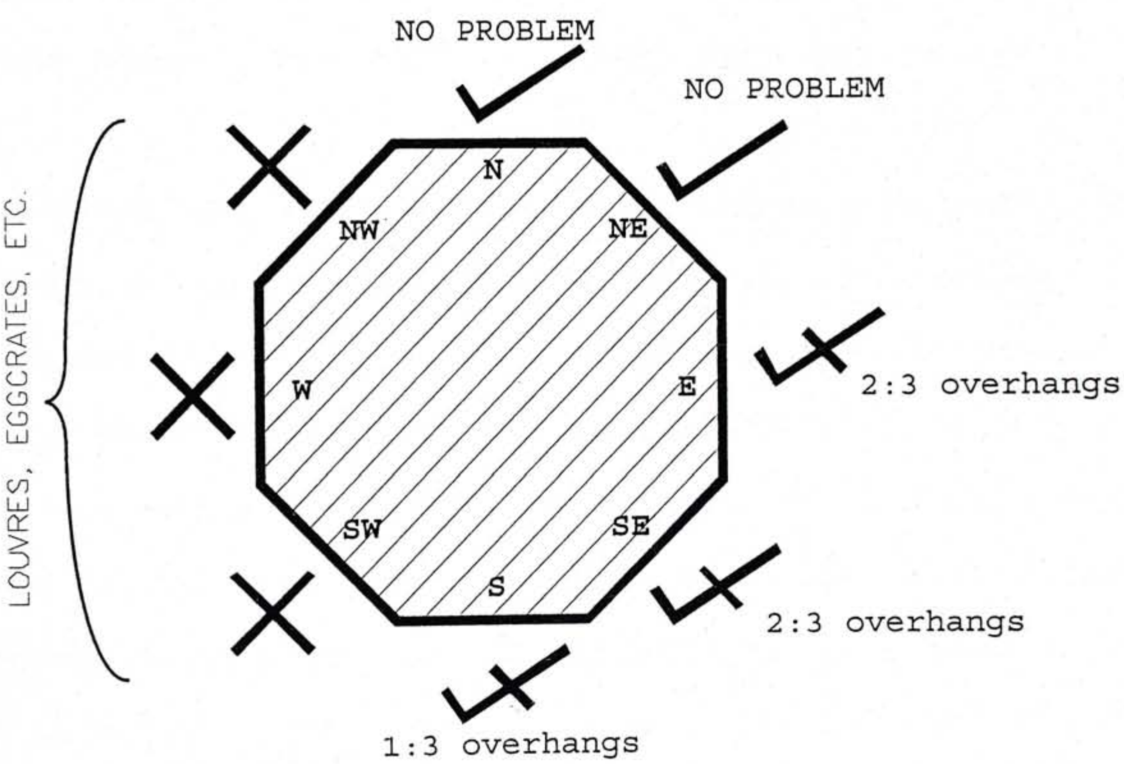
8) Ventilation rates are found to be optimum at 8 to 16 air changes per hour. A combination of ceiling and exhaust fans for each room will help to achieve this. Care should be taken to choose an exhaust fan that has its motor facing outside the house while blowing out, so as not to add the heat generated by itself into the room. Not much can be done about the heat generated by a conventional ceiling fan, however, due to its very location.

9) During the hot periods of the day (between 10:00 and 21:00 hours), fans used for bringing in air should be turned off, or else they will bring in external air that is hotter than the interior. (Ideally such fans should be controlled by sensors[30] that simultaneously monitor indoor and outdoor air temperatures. They will work best if the sensors are programmed to switch off the fans when the latter is greater.)



30. Such sensors retail for about US$ 40 in Hong Kong. This is expensive for low cost Indian homes but, if made locally, would probably sell at more affordable prices. How would users be affected by such "programmed" fans? Especially on a day when a fan keeps switching on and off if outside temperatures fluctuate rapidly on either side of a set point? (One of the suggestions to overcome this is to also program the fan not to react more than once until a certain time interval has lapsed.) These are questions worthy of further study.

10) The critical directions for avoiding openings on facades are northwest, west and southwest. The ideal directions for having openings are north and northeast. Openings can be provided on facades facing south, provided shallow shading devices (ratio of overhang to window height around 1:3) are used. If moderate shading devices (a ratio of around 2:3) are used then openings can be made in southeast and east facades.



If openings cannot be avoided upon the facades from northwest to southwest, then shading devices have to be deep (ratios of 1:1 or greater) or carefully designed (louvers, egg crates, operable or otherwise, etc.) to see that direct solar gain into the rooms is excluded.

5.2 A validation of the results using a model of a complete housing unit

The exercises conducted produced a set of results. The findings from these results were applied to the model of a complete housing unit as described in 1.1 earlier. Stage I of the five stages of the growing unit was modelled on DEROB (Fig. 28). Stage I was chosen for simplicity as at this stage there are just four volumes in the house - the hall, kitchen, bath and toilet.

This model was duplicated. One of the models was dubbed a 'Bad-house' and the other was dubbed a 'Good-house'. In the 'Good-house' the design guidelines were followed - the orientation was due south, the external walls were made one and a half brick thick (345 mm) and coloured light (0.33), the roof was coloured white (0.10), the openings were shaded well, air changes were kept at 8.0 and switched off between 10:00 and 22:00 hours. The 'Bad-house' followed none of these guidelines[31]. It was oriented due east, the walls were made just one brick thick and coloured dark (0.66), the colour of the roof was also kept dark (0.66), air change rates were kept at just 1.0 and were not switched off at any time of the day.

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31. While such demarcations between "good" and "bad" appear to be drastic, this was done in order to appreciate the magnitude of the problem, when the effects of all the "bad" bits are accumulated. Although a small percentage of "good" houses may have been built, "bad" houses form the greater percentage. The eventual goal, anyway, is to build a "good" house.

In both cases, parapet walls were included as shading walls. Internal loads were added based upon occupancy and activity (refer section 1.3). The three week special weather file was used for the simulation period. Cooling thermostats were set at 28.0°C between 6:00 and 22:00 hours. The living spaces in the house were monitored. Simulations were run and it can be seen from the accompanying graphs (Fig. 29) that there is a considerable drop in cooling energy required for the 'Good-house' as compared to the 'Bad-house'.

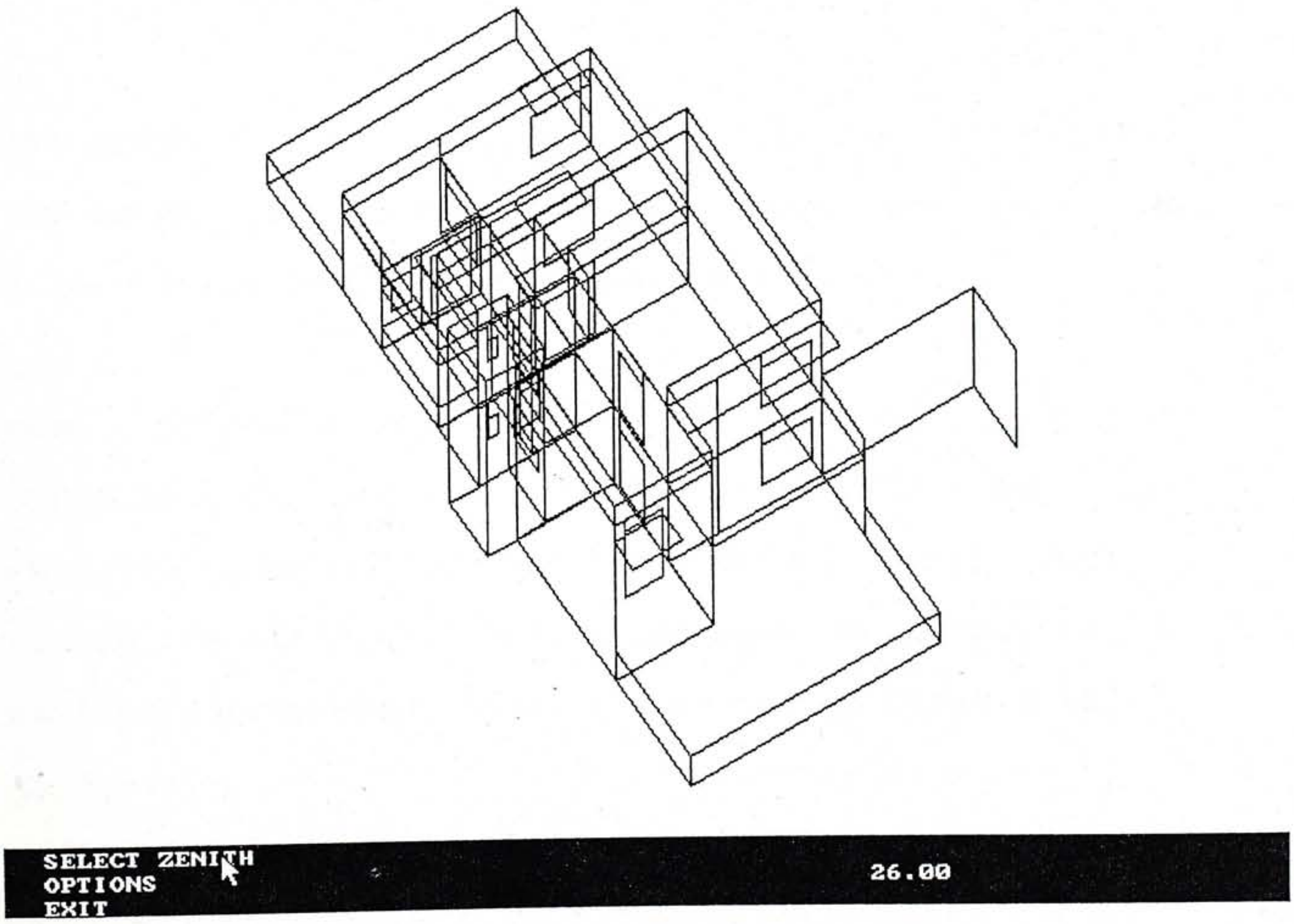

Fig. 28: The MIG unit as portrayed in DEROB[32]

32. After the geometric descriptions (DIG) file is run in DEROB, one of the output files generated (refer Fig. 10: DEROB IUA 1.0 Flow Chart) contains information tailored for use with the graphics module of a program known as GIOTTO (Higgs, 1991). This allows one to set up

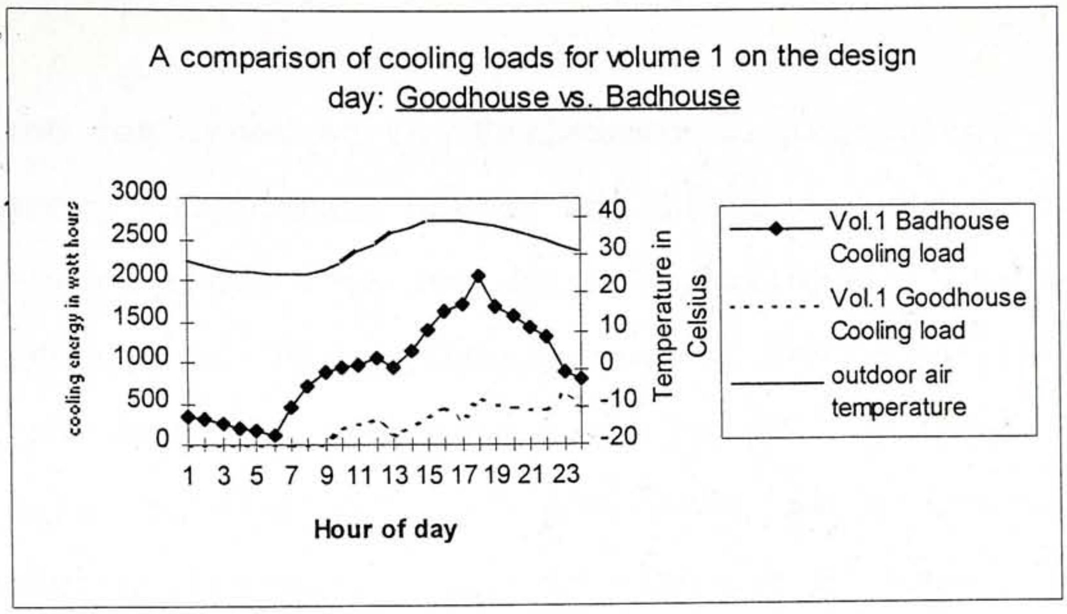

Fig. 29: Performance of the unit after following guidelines

The graph in Fig. 29 for volume 1 (the hall) indicates the extent of improvement in the thermal performance of a house if the design guidelines are followed.

Also, the cooling energy used for the whole unit for the three week period is around 133 kWh for the 'Good-house' while it is around 425 kWh for the 'Bad-house'. The cumulative effects of bad design show up sharply in cooling energy used. This is more than a three fold increase.

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viewpoints and check if the geometric description is representative of the building under study.

5.3 Afterword

Research continues at the Environmental Technology Laboratory to generate better and quicker ways to cover ground with respect to evaluating a building's thermal performance. Dr. Higgs' development of design guidelines using the Energy Design Technique, or EDT, for any particular climate (Hand & Higgs, 1987) is in the process of becoming streamlined for use with the PC under the MS-Windows environment. The first batch of undergraduate students to use this tool during the spring term, '95, has given impetus to the process. Alongside these happenings, a more sophisticated version of the program dealing with Fanger's thermal comfort equation has been created, also to run under the MS-Windows environment. The interested user can use this to predict the PPD for any of the six variables while manipulating the other five. Meanwhile, sensitivity studies for a variety of building materials and combinations thereof are being undertaken.[33] On the 'tangible' side, affordable instrumentation is being researched into, as also the development of climate monitoring instruments *interfaced to PCs* for long term data collection and management.

33. As the results of sensitivity studies on DEROB are dependent upon accurate weather data, there will be a thrust towards creating a reliable weather database.

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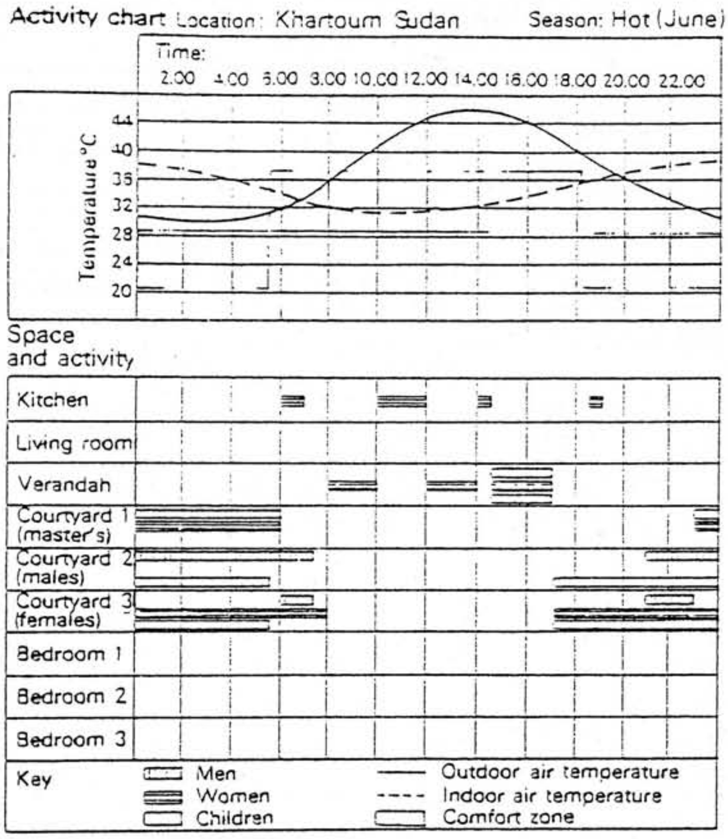
7.0 APPENDICES

7.1 APPENDIX A: Activity chart

(Koenigsberger et al , 1974).

Activity chart
(Khartoum, Sudan – hot season, June)



NOTES

1. Men go to work at 7.30 and return at 14.30 hours (time spent at work is from 8.00 to 14.00 hours).
2. Children go to school at 7.30 and return at 14.30 hours (time spent at school is from 8.00 to 14.00 hours).
3. The verandah is used as a dining area at lunch time and as a sleeping space during the afternoon siesta.
4. Courtyard 1 is used at night as a sleeping area by parents only.
5. Courtyard 2 is used to entertain male visitors in the evening. At night it is used as a sleeping space by the male members of the household.
6. Courtyard 3 is used to entertain female visitors. The whole family takes breakfast and dinner here. At night it is used as a sleeping space by the female members of the household.

7.2 APPENDIX B: Clo values

Although there is no commonly accepted Clo standard, the following values are adopted by ASHRAE Standards. These values were determined at Kansas State University using a static copper mannequin (Bradshaw, 1993).

Clo values for individual items of clothing:

MEN		WOMEN	
Clothing	clo	Clothing	clo
Underwear		Underwear	
Sleeveless	0.06	Girdle	0.04
T-shirt	0.09	Bra and panties	0.05
Briefs	0.05	Half slip	0.13
Long underwear -Upper	0.10	Full slip	0.19
Long underwear -Lower	0.10	Long underwear-Upper	0.10
Shirt		Long underwear-Lower	0.10
Light, short sleeve	0.14	Blouse	
long sleeve	0.22	Light, long sleeve	0.20
Heavy, short sleeve	0.25	Heavy, long sleeve	0.29
long sleeve	0.29	Dress, light	0.22
Vest, light	0.15	Dress, heavy	0.70
Vest, heavy	0.29		
		Skirt, light	0.10
Trousers, light	0.26	Skirt, heavy	0.22
Trousers, heavy	0.32	Slacks, light	0.10
		Slacks, heavy	0.44
Sweater, light	0.20	Sweater,	
Sweater, heavy	0.37	light, sleeveless	0.17
Jacket, light	0.22	heavy, long sleeve	0.37
Jacket, heavy	0.49	Jacket, light	0.17
Socks		Jacket, heavy	0.37
Ankle length, thin	0.03	Stockings	
thick	0.04	Any length	0.01
Knee high	0.10	Pantyhose	0.01
Shoes		Shoes	
Sandals	0.02	Sandals	0.02
Oxfords	0.04	Pumps	0.04
Boots	0.08	Boots	0.08
Hat and overcoat	2.00	Hat and overcoat	2.00

Clo = 0.82 ($\sum$ clo individual items)

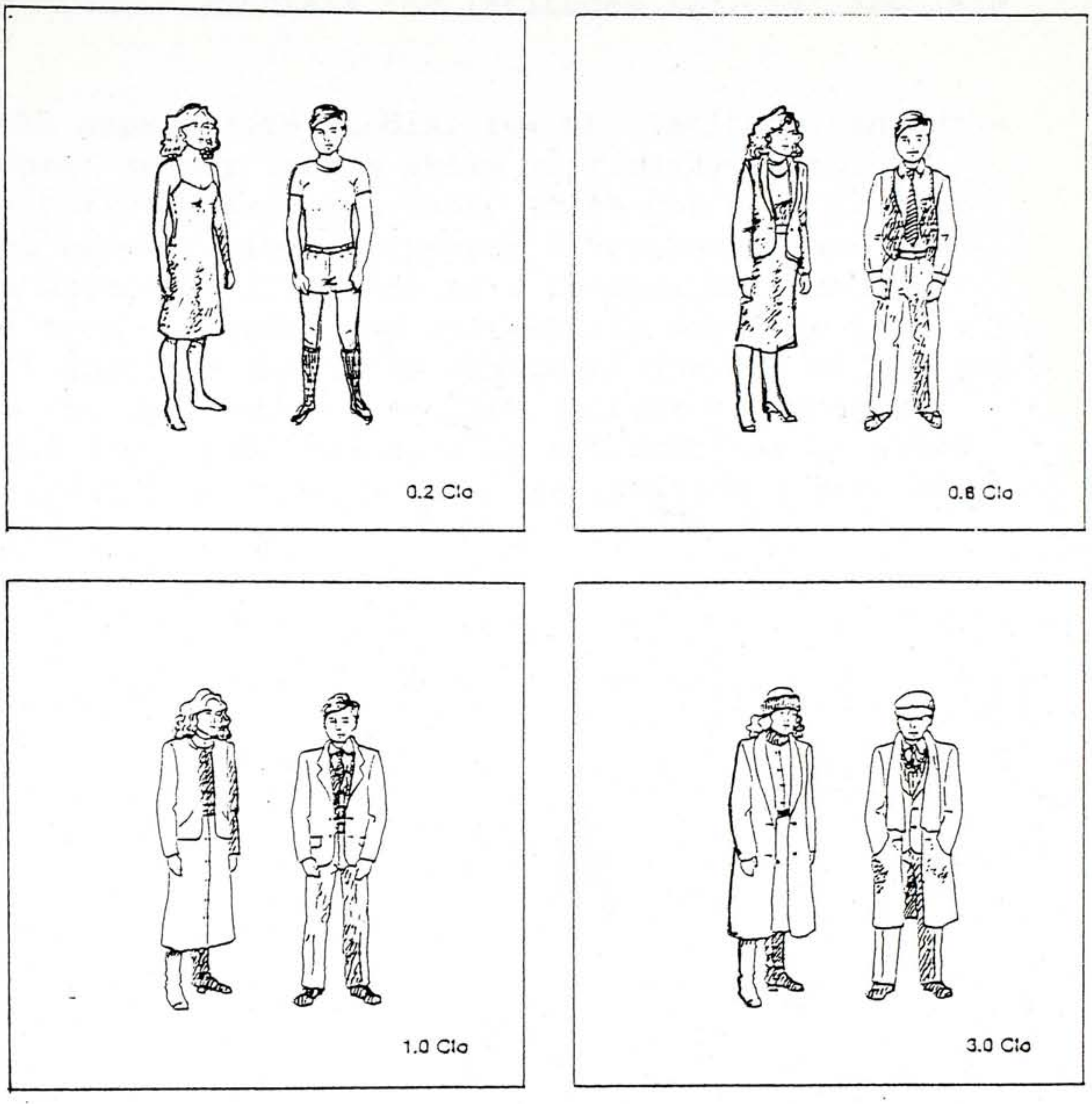
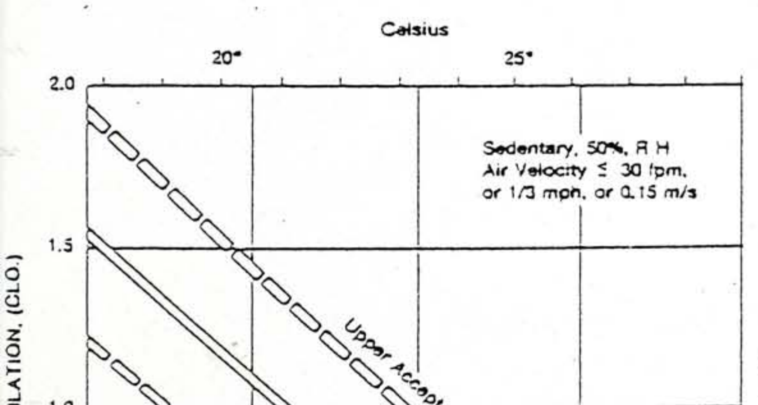
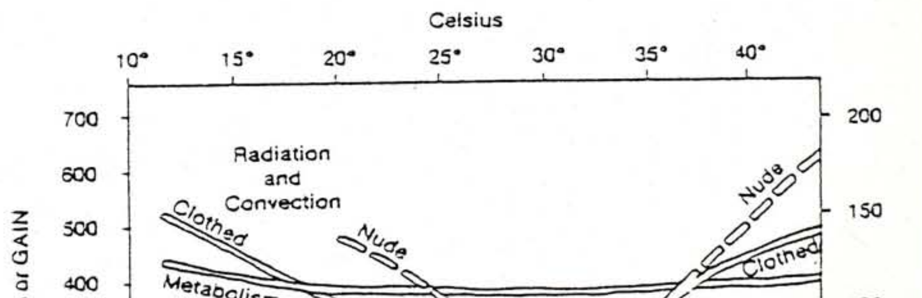


Illustration of a range of clo values.



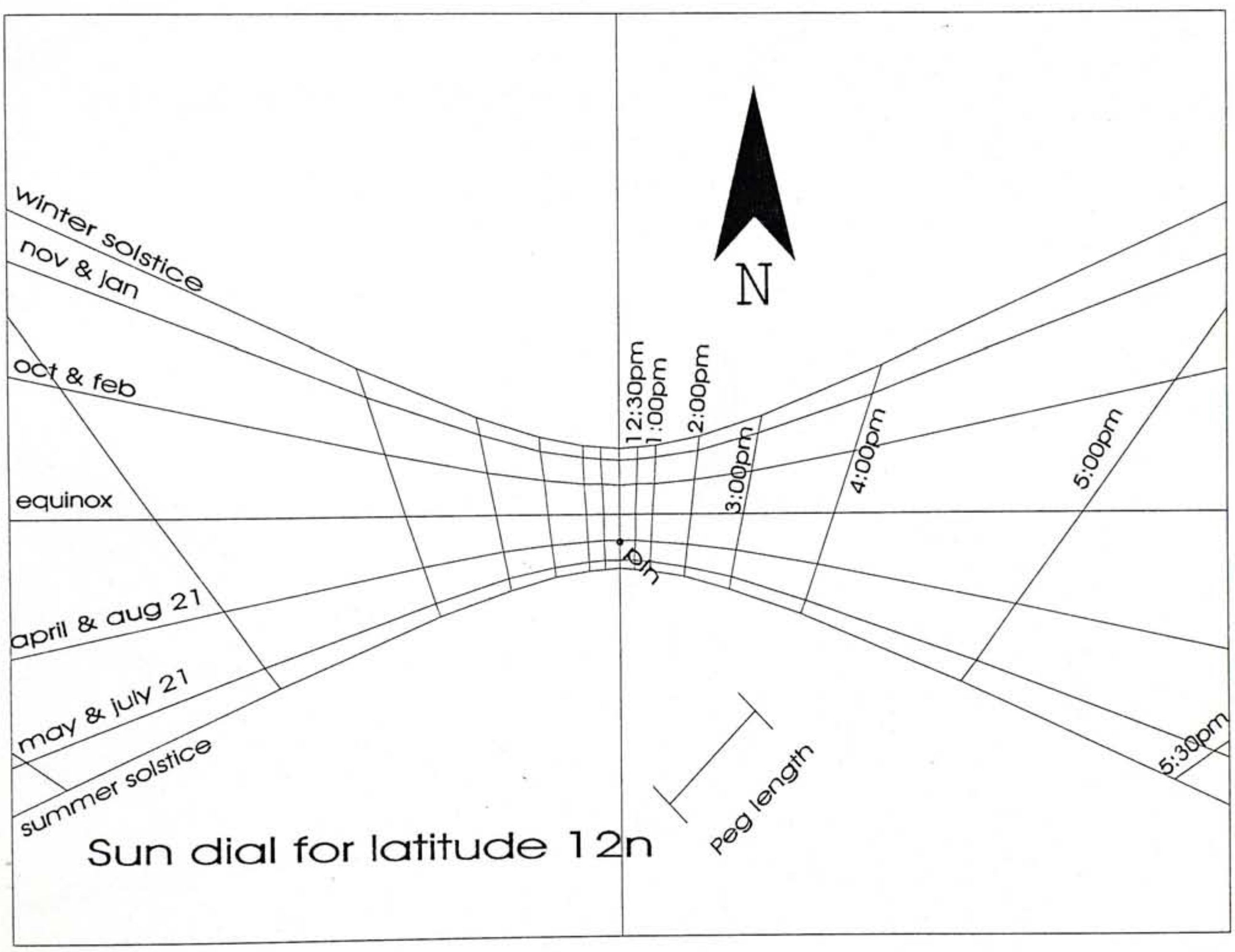
Clothing level (in clo units) necessary for comfort at different operative temperatures. Reprinted from Standard 55 by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

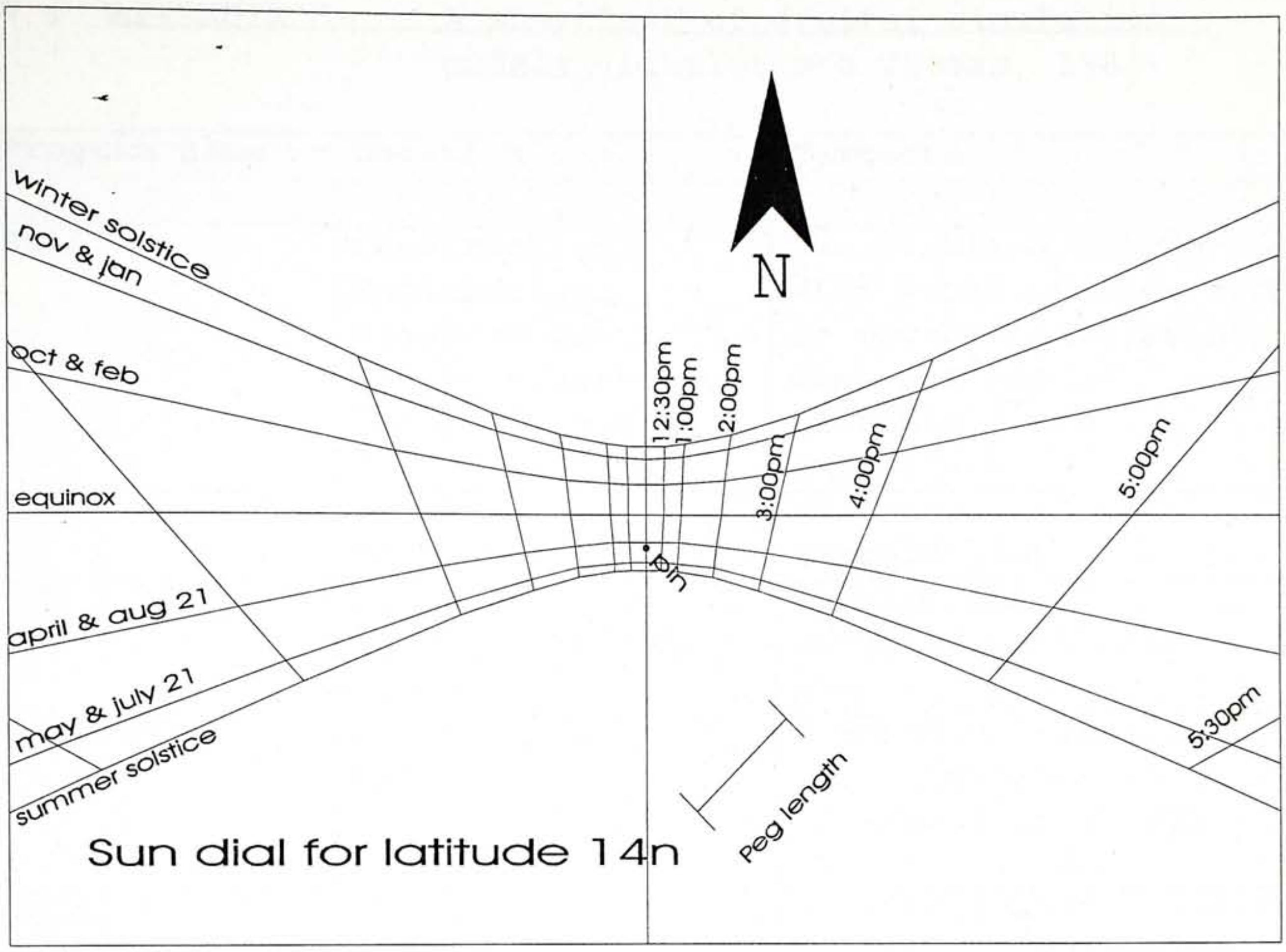


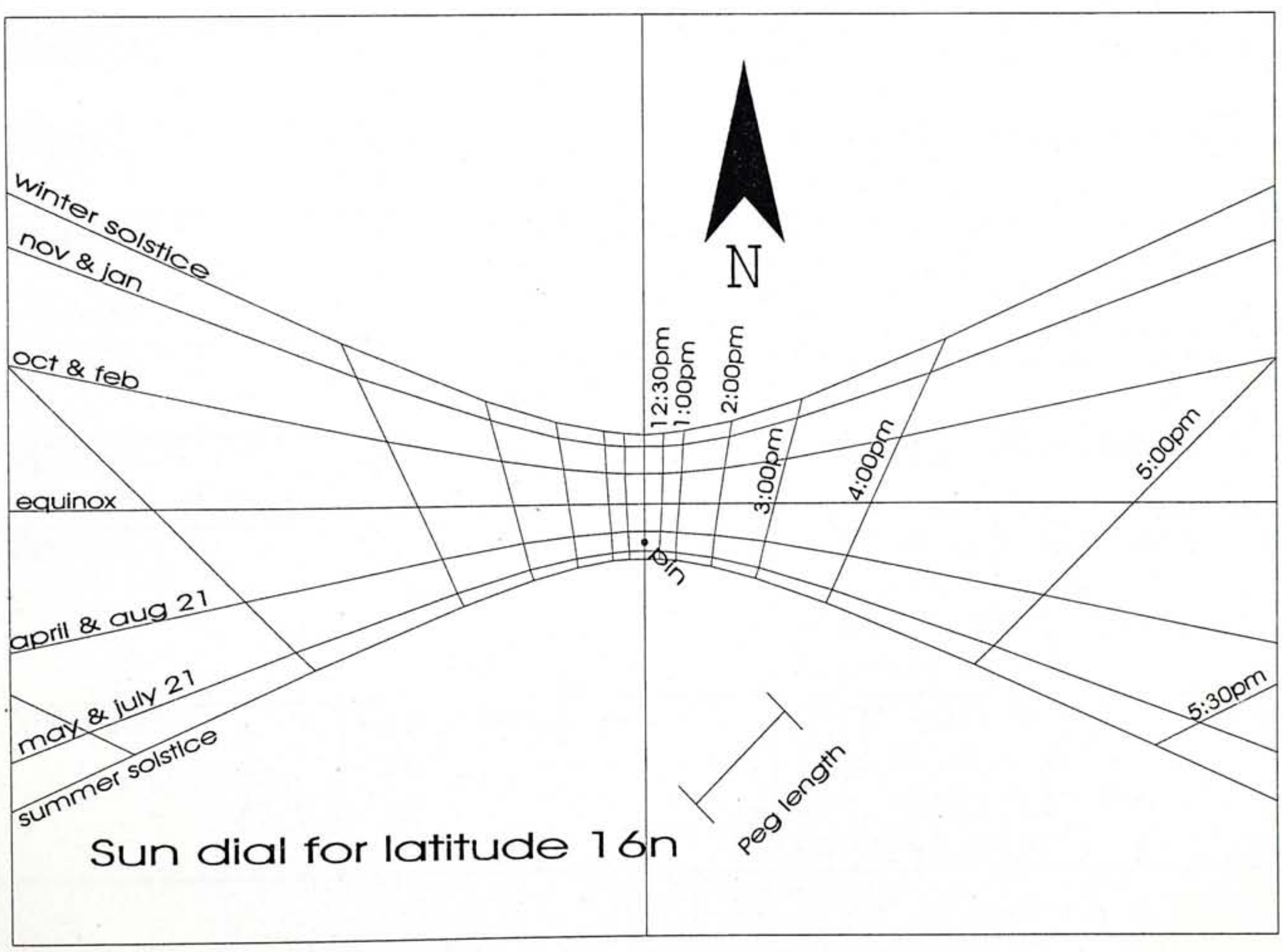
Relationship between metabolism, evaporation, radiation, convection, and temperature.

7.3 APPENDIX C: Sundials for latitudes 12°, 14° and 16°N

Choose the appropriate sundial for the latitude. Insert a gnomon (peg) as per length shown *vertically* at point marked - this is very important. Place the dial flat on the model base, facing the proper direction. Place the model in direct sunlight (or at a considerable enough distance from a bright lamp so that its rays are nearly parallel) and tilt until the shadow of the tip of the peg falls at the desired intersection of hour and season lines. The light will now fall on the model as it would in reality at that hour, season and latitude (Lynch and Hack, 1984).




N
winter solstice
nov & jan
oct & feb
equinox
april & aug 21
may & july 21
summer solstice
12:30pm
1:00pm
2:00pm
3:00pm
4:00pm
5:00pm
5:30pm
pin
Peg length
Sun dial for latitude 14n


N
winter solstice
nov & jan
oct & feb
equinox
april & aug 21
may & july 21
summer solstice
12:30pm
1:00pm
2:00pm
3:00pm
4:00pm
5:00pm
5:30pm
pin
Peg length
Sun dial for latitude 16n

7.4 APPENDIX D: A shortlist of digital simulation models (Littler and Thomas, 1984)

Program name	Location	Comments
BLAST	Construction Engineering. Research Lab, Lawrence Berkeley Lab (US); Boeing CDC, UK	Has problems coping with rapid changes such as movable insulation; does not handle variable glass emissivity
DEROB	Univ. Austin, Texas (US)	see section 3.0 (Methodology)
DOE 2.1	Los Alamos Lab, Lawrence Berkeley Lab (US)	Remains heavily weighted with HVAC plant
FREHEAT	Colorado State Univ., (US)	Limited documentation, only one zone, only mass wall or direct gain
SOLAR 5.0	UCLA, (US)	Primarily an excellent building description model, not an 'energy' model
SUNCODE	Ecotope Inc., Seattle (US)	Self shading routines only
SYRSOL	Syracuse Univ., (US)	Uses only the sol-air method
TRNSYS	Univ. Washington, Seattle	Heavily weighted towards active solar systems
2-ZONE	Lawrence Berkeley Lab, (US)	Limited to two zones
UWENSOL	Univ. Washington, Seattle	Not well documented
ESP-r	Univ. Strathclyde, (UK)	Good documentation; availability on a commercial basis is expensive
SUNSPOT	Los Alamos Lab, (US)	Excellent research tool for direct gain (but not organized for general users)

Program name	Location	Comments
PASOLE	Los Alamos Lab, (US)	Excellent research tool for mass walls (but not organized for general users)
THERM	Watson House, London	Boundary temperatures are the wall surfaces, not air temperatures; limited shading routine
TASS	Cranfield, (UK)	Excellent input and output but less detailed in its handling of other problems
BEEP	Central Electricity Generation Board (UK)	Private code not accessible for changes or inspection of methods; incomplete documentation, not user friendly
BUILD	Univ. Nottingham, (UK)	
HOUSE	Electricity Council Research Centre, (UK)	Only deals with 4 day slots
NBSLD	National Bureau of Standards, (US)	Superseded by BLAST
UWIST	Univ. Wales, (UK)	Not documented
BRISTOL	Univ. Bristol, (UK)	Being analogue, presently difficult to alter
UMIST, hybrid	Buildings Dept., Univ. Manchester	

7.5 APPENDIX E: Weather data for Chitradurga district.

Weather data for Chitradurga district has been maintained since the turn of the century at the only meteorological station in existence in the town of Chitradurga. The collected data is also archived at the Central Observatory as well as the Indian Meteorological Department, both located at Bangalore. Some of the data reproduced here was copied by hand at the Central Observatory as well at the Indian Meteorological Department.

[The first part (pp. 134 & 135), which is a general description of Chitradurga's weather, has been re-typed word for word, as the original document was received in poor condition.]

CHITRADURGA DISTRICT

The climate of this district which is in the southwestern part of the Deccan plateau is marked by hot summer months, low rainfall and a pleasant monsoon season. December to February is the cold season with clear bright weather generally. The hot season starts in March and lasts till about the beginning of June when the district comes under the influence of the southwest monsoon. The southwest monsoon season extends upto September; October and November form the retreating monsoon or post-monsoon season.

RAINFALL

The district has a network of none rain gauge stations with records for periods ranging from 87 to 110 years. The statement of the rainfall at these stations and for the district as a whole are given in tables 1 and 2. The average annual rainfall over the district is 579.3 mm. Rainfall decreases in general from the southwest to the northeast. The district receives rainfall both during the southwest monsoon season (June to September) and the retreating monsoon (October and November). 50% of the annual rainfall is received during the southwest monsoon season. Rainfall in October and November account for about 30% of the annual rainfall. October is the month with the maximum amount of rainfall. The variation in the annual rainfall of the district is large. In the fifty one year period 1901 to 1950, the highest annual rainfall, amounting to 159% of the normal, occurred in 1933. 1908 was the year with the lowest rainfall which amounted to 61% of the normal. In the same fifty year period rainfall less than 80% of the normal occurred in 12 years, two of them being consecutive. But at individual stations there have been even four or five occasions when two consecutive years had less than 80% of the normal rainfall. It will be seen from table 2 that the rainfall in the district was between 400 and 700 mm in 40 years out of 50.

On an average there are 40 rainy days (i.e. days with rainfall of 2.5 mm or more). This number varies from 29 at Challakere to 49 at Belalkere.

The highest rainfall in 24 hours recorded at any station in the district was 215.9 mm at Challakere on 1888 May, 12.

TEMPERATURE

The only meteorological observatory in this district is at Chitradurga which has been in existence for over 68 years. The meteorological data of this station may be taken as representative of the conditions in the district. The period from about the latter half of November to February is one of comparatively cool weather, December being the coldest month with the mean daily maximum temperature at 28.0°C and the mean daily minimum at 16.7°C. The period from March to May is one of increasing temperature, April is the hottest month with the mean daily maximum temperature at 36.3°C. During this season the maximum temperature may sometimes reach 41.0° C. With the advance of the monsoon air over the district, early in June, temperatures drop and the weather becomes more pleasant. There is a slight increase of temperature in October and thereafter both day and night temperatures begin to drop. the highest maximum temperature ever recorded at Chitradurga was 41.7°C on 1931 May, 31 and the lowest minimum 8.3°C on 1945 November, 28 and 1945 December, 11.

HUMIDITY

Relative humidity is high about 70% during the period June to November. In the rest of the year, particularly in the summer months, the relative humidities are low and come down to less than 30% in the afternoons.

CLOUDINESS

During the period from June to about the end of October skies are generally heavily clouded to overcast. In the rest of the year they are clear or lightly clouded.

WINDS

Winds are generally moderate with some strengthening in the southwest monsoon months. In the southwest monsoon months they blow mainly from a southwesterly or westerly direction. In the rest of the year they are predominantly from directions between northeast and southeast.

SPECIAL WEATHER PHENOMENA

Thunderstorms are frequent in the summer months of April and May and, to a lesser extent, in the southwest monsoon months. In September and October they are more frequent than in the other monsoon months. Some of the cyclonic storms which originate in the Bay of Bengal during the post monsoon months cross the eastern coast, often weaken into depressions and move across the peninsula. When these pass through the district or its neighbourhood, the district gets widespread rain.

Tables 3, 4 and 5 give the data of temperature and humidity, mean wind speed and special weather phenomena, respectively for Chitradurga.

***

TABLE - 1

NORMAL AND EXTREME RAINFALL

Station	No. of years of data		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Highest annual rainfall as % of normal & year **	Lowest annual rainfall as % of normal & year **	Heaviest rainfall in 24 hours * Amount (mm)	Date
Chitradurga	50	a	6.1	5.1	4.3	21.1	79.3	61.7	74.4	89.4	101.8	120.7	59.2	15.2	638.1	166 (1933)	46 (1945)	181.6	1955 May 21
		b	0.3	0.3	0.4	1.9	4.5	4.9	8.6	7.5	6.9	6.5	3.5	0.8	46.1				
Challakare	50	a	3.3	5.8	4.1	19.1	58.7	29.7	33.3	62.2	92.2	100.1	38.1	8.9	455.5	176 (1933)	37 (1920)	215.9	1888 May 12
		b	0.3	0.4	0.3	1.3	3.7	2.4	3.5	3.8	5.3	5.0	2.6	0.6	29.2				
Hiriyur	50	a	3.3	5.1	2.0	23.4	76.7	40.4	46.5	65.3	97.5	111.0	53.3	9.1	533.6	200 (1917)	55 (1945)	138.4	1897 Sep 30
		b	0.3	0.3	0.3	1.7	4.6	2.9	4.1	4.5	5.5	5.9	2.9	0.6	33.6				
Holalkere	50	a	6.3	5.6	5.8	29.5	80.5	56.9	87.9	91.9	99.3	122.2	53.1	14.0	653.0	188 (1933)	59 (1945)	146.1	1931 Nov 7
		b	0.4	0.3	0.5	2.3	4.9	5.0	9.7	8.7	7.1	6.7	3.1	0.7	49.4				
Davangere	50	a	2.5	4.1	3.1	28.7	71.9	69.6	91.4	75.2	109.5	126.0	47.2	10.7	639.9	139 (1932)	46 (1906)	190.5	1891 Jun 18
		b	0.2	0.3	0.3	2.2	3.9	5.9	9.6	7.4	6.7	6.4	2.5	0.6	46.0				
Molakalmuru	50	a	2.5	5.1	3.1	19.1	63.3	52.6	47.7	81.8	139.7	118.6	48.0	7.4	588.9	171 (1917)	52 (1911)	182.1	1948 Aug 3
		b	0.4	0.3	0.3	1.4	4.0	3.9	4.3	5.3	6.4	5.7	3.0	0.4	35.4				
Jagalur	50	a	4.1	6.6	3.1	22.9	65.5	48.3	63.7	75.9	103.9	97.3	45.5	8.1	544.9	211 (1932)	45 (1942)	177.3	1932 Nov 7
		b	0.3	0.3	0.3	1.7	4.1	4.1	7.0	5.9	6.2	5.5	2.7	0.9	38.6				
Hosadruga	50	a	3.1	4.8	4.6	23.1	90.9	55.6	70.6	65.8	82.8	125.0	66.5	13.5	806.3	184 (1933)	56 (1908)	203.2	1955 Oct 21
		b	0.3	0.3	0.4	1.8	5.3	4.0	7.2	5.6	5.6	6.7	3.5	0.8	41.5				
Harihar	50	a	3.8	3.1	2.8	28.5	68.3	55.1	69.6	65.3	95.5	105.4	44.5	11.7	953.6	171 (1917)	50 (1908)	198.1	1943 May 21
		b	0.2	0.2	0.3	2.3	4.1	4.9	8.1	6.3	5.7	5.8	2.6	0.5	41.0				
Chitradurga (District)		a	3.9	5.0	3.7	23.9	72.8	52.2	65.0	74.8	102.4	114.0	50.6	11.0	579.3	159 (1933)	61 (1908)		
		b	0.3	0.3	0.3	1.8	4.3	4.2	6.9	6.1	6.2	6.0	2.9	0.6	39.9				

(a) Normal rainfall in mm. (b) Average number of rainy days (days with rain of 2.5 mm or more).

* Based on all available data upto 1970. ** Years given in brackets.

TABLE - 2

FREQUENCY OF ANNUAL RAINFALL IN THE DISTRICT

(Data 1901 - 1950)

Range in mm.	No.of years	Range in mm.	No.of years
301 - 400	2	701 - 800	5
401 - 500	15	801 - 900	1
501 - 600	12	901 - 1000	2
601 - 700	13		

TABLE - 3

NORMAL TEMPERATURE AND RELATIVE HUMIDITY

(CHITRADURGA)

Month	Mean Daily Max.	Mean Daily Min.	Highest Max. ever recorded		Lowest Min. ever recorded		Relative Humidity 0830	Relative Humidity 1730*
	°C	°C	°C	Date	°C	Date	%	%
January	28.9	17.1	33.9	1900 Jan 29	9.9	1975 Jan 8	65	33
February	32.0	19.2	36.1	1931 Feb 28	13.3	1947 Feb 6	56	24
March	34.9	21.5	38.9	1925 Mar 31	14.7	1976 Mar 2	55	24
April	36.3	22.7	39.4	1941 Apr 19	16.4	1978 Apr 24	67	30
May	35.1	22.3	41.7	1931 May 21	16.7	1951 May 25	75	39
June	30.6	21.4	37.8	1935 Jun 6	17.2	1906 Jun 6	79	63
July	28.1	20.8	34.4	1932 Jul 3	17.8	1943 Jul 10	83	69
August	28.1	20.5	32.8	1932 Aug 17	17.8	1955 Aug 16	84	69
September	29.1	20.3	35.0	1905 Sep 30	15.0	1910 Sep 19	83	63
October	29.6	20.3	35.0	1965 Oct 10	14.9	1974 Oct 29	79	55
November	28.4	18.4	32.8	1931 Nov 2	8.3	1945 Nov 28	73	50
December	28.0	16.7	32.8	1930 Dec 24	8.3	1945 Dec 11	71	40
Annual	30.8	20.1					73	47

* Hours I.S.T.

TABLE - 4

MEAN WIND SPEED IN KM/HR.

(CHITRADURGA)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
7.8	6.9	7.1	7.7	10.6	14.2	14.9	13.1	10.8	6.3	6.2	7.6	9.4

TABLE - 5

SPECIAL WEATHER PHENOMENA

(CHITRADURGA)

Mean No.of days with*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Thunder	0.1	0.2	1.1	5.0	6.0	1.1	0.1	0.9	3.0	3.0	0.5	0.1	21.0
Hail	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2
Dust-Storm	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Squall	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fog	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1

* No.of days 2 and above are given in whole numbers.

METEOROLOGICAL DATA

STATION CHITRADURGA

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1984												
Mean Maximum Temperature (°C)	29.6	30.9	33.3	35.6	36.2	29.6	27.6	27.9	29.6	28.6	28.1	28.6
Mean Minimum Temperature (°C)	18.2	19.7	21.2	22.7	23.0	21.4	20.8	20.3	20.2	20.4	17.2	17.2
Total Rainfall (mm)	0.0	0.2	32.8	44.6	43.7	77.1	61.2	21.8	112.5	123.3	2.3	7.5
Highest Maximum Temperature (°C)	31.4	34.3	36.7	36.8	38.8	34.6	31.1	30.5	31.9	30.8	30.0	30.7
Lowest Minimum Temperature (°C)	14.5	16.4	14.7	19.8	20.3	19.7	20.1	19.5	19.0	18.7	12.4	12.9
Heaviest Rainfall in 24 hrs (mm)	0.0	0.2	15.9	13.7	23.1	29.4	8.8	4.5	54.0	44.9	1.7	7.1
1985												
Mean Maximum Temperature (°C)	29.9	32.4	35.7	35.9	35.4	28.8	28.5	27.9	30.2	28.9	29.1	29.2
Mean Minimum Temperature (°C)	18.5	19.2	22.2	22.9	22.5	21.0	20.7	20.4	20.3	19.4	17.6	18.4
Total Rainfall (mm)	0.0	0.0	9.5	23.7	100.1	57.8	34.7	61.6	62.6	39.9	2.3	0.7
Highest Maximum Temperature (°C)	31.5	34.2	36.8	38.1	38.1	32.4	31.3	30.2	32.5	30.8	31.7	30.9
Lowest Minimum Temperature (°C)	15.6	15.5	18.5	19.6	17.4	20.0	20.0	19.8	18.9	14.2	14.4	15.3
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	8.9	20.6	71.8	11.1	10.2	10.7	18.5	12.8	1.1	0.4
1986												
Mean Maximum Temperature (°C)	27.5	31.2	35.0	37.2	35.8	30.8	29.0	27.4	29.8	30.4	28.6	28.7
Mean Minimum Temperature (°C)	16.8	19.1	22.4	23.6	22.6	21.7	21.0	20.2	20.4	21.0	19.3	18.3
Total Rainfall (mm)	23.0	20.3	3.8	2.4	16.2	59.2	38.8	84.5	155.3	38.0	70.0	3.7
Highest Maximum Temperature (°C)	30.0	32.2	37.4	39.3	37.3	35.3	31.8	30.4	31.6	32.8	30.5	31.5
Lowest Minimum Temperature (°C)	13.3	15.7	17.6	20.7	20.1	20.5	19.9	19.3	18.8	18.2	15.4	15.0
Heaviest Rainfall in 24 hrs (mm)	12.6	9.2	3.8	1.0	11.5	16.3	19.3	20.8	31.6	18.3	25.0	1.9

js/-

Shrinaik: This is 10 year data for Chitra Durga.
These are the details available with Meteorological Centre.
If you need the data for more years, kindly let me
know. Ring up for the receipt. All well

Yours

Meteorologist,
Central Observatory,
Palace Road, Bangalore-1

Meteorologist, 28-2-54
Central Observatory,

P.S. one copy is also being sent by Mail.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					1987							
Mean Maximum Temperature (°C)	29.0	30.8	34.2	37.0	35.5	30.7	29.9	28.9	30.4	29.1	27.9	26.4
Mean Minimum Temperature (°C)	17.6	18.3	21.0	23.2	22.9	21.7	21.5	21.3	21.1	20.8	18.9	17.3
Total Rainfall (mm)	0.0	0.0	0.0	12.9	109.7	52.5	17.3	133.0	211.0	172.2	68.8	84.4
Highest Maximum Temperature (°C)	30.6	34.2	36.6	39.4	37.7	34.9	32.9	32.0	33.2	30.8	30.6	29.7
Lowest Minimum Temperature (°C)	14.0	14.4	17.0	20.2	19.3	30.6	20.3	20.2	19.5	17.2	12.6	11.6
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	0.0	6.7	29.2	12.8	5.8	53.5	61.4	61.5	29.5	25.8
					1988							
Mean Maximum Temperature (°C)	28.3	32.8	34.5	33.4	34.8	31.3	27.8	28.2	28.8	29.9	29.1	27.4
Mean Minimum Temperature (°C)	18.2	19.9	21.9	22.8	22.8	21.9	21.3	21.0	21.8	20.2	19.3	16.2
Total Rainfall (mm)	0.0	0.0	0.0	51.8	111.1	45.8	70.5	264.0	253.7	0.9	TRACE	25.3
Highest Maximum Temperature (°C)	31.0	35.3	37.2	37.2	38.0	33.6	32.8	31.3	30.9	31.5	30.6	29.6
Lowest Minimum Temperature (°C)	13.5	14.0	19.4	19.4	19.9	20.7	20.0	19.3	19.2	15.0	12.9	10.4
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	0.3	14.6	39.0	1.4	18.1	72.4	96.8	0.8	Trace	16.9
					1989							
Mean Maximum Temperature (°C)	28.9	32.5	33.5	35.8	35.1	29.7	28.0	27.4	29.3	30.6	29.0	27.9
Mean Minimum Temperature (°C)	16.3	17.1	20.1	22.7	22.3	21.2	20.8	20.4	20.3	20.0	18.8	17.3
Total Rainfall (mm)	0.0	0.0	9.8	15.9	62.5	48.8	95.7	59.3	138.5	7.6	59.2	32.6
Highest Maximum Temperature (°C)	31.5	34.2	35.5	37.9	38.1	35.1	32.5	29.7	32.0	31.8	31.1	31.7
Lowest Minimum Temperature (°C)	12.3	13.6	15.7	20.6	12.6	19.8	19.4	19.6	17.6	14.9	14.5	14.2
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	6.8	10.3	45.6	22.4	20.1	17.3	49.1	7.2	55.8	31.8
					1990							
Mean Maximum Temperature (°C)	29.4	32.0	34.3	36.9	32.9	29.5	27.5	27.3	29.7	29.5	27.8	27.7
Mean Minimum Temperature (°C)	15.8	19.4	21.4	23.5	22.1	21.4	20.5	20.8	20.5	20.7	18.9	17.1
Total Rainfall (mm)	0.0	0.0	0.0	2.6	104.6	38.3	66.5	41.2	6.5	137.2	69.8	4.8
Highest Maximum Temperature (°C)	31.6	33.9	36.2	38.9	37.2	32.1	30.7	30.7	31.8	33.2	29.8	29.4
Lowest Minimum Temperature (°C)	12.8	17.0	18.7	20.9	19.8	20.2	19.3	19.7	19.4	19.5	13.1	14.4
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	0.0	2.6	68.7	17.0	15.0	7.6	3.4	97.4	41.1	4.6

js/-

28.2.94

Meteorologist,
Central ...

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	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1991												
Mean Maximum Temperature (°C)	30.6	32.6	36.2	35.7	35.3	28.3	26.3	26.5	29.5	29.5	27.0	27.6
Mean Minimum Temperature (°C)	17.8	19.9	22.4	22.7	22.8	22.1	20.9	20.4	20.5	20.1	17.9	16.6
Total Rainfall (mm)	0.0	0.0	6.2	32.7	131.3	100.0	62.1	80.8	75.3	148.5	71.1	0.0
Highest Maximum Temperature (°C)	32.0	34.2	38.0	39.0	38.0	34.8	29.5	28.4	33.1	33.0	29.5	31.0
Lowest Minimum Temperature (°C)	13.2	17.0	19.5	18.4	18.8	20.2	19.6	19.6	19.2	15.7	10.4	13.9
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	6.2	9.2	50.8	39.0	10.1	10.2	31.0	37.0	20.8	0.0
1992												
Mean Maximum Temperature (°C)	28.8	32.2	36.1	36.8	35.0	29.9	27.9	27.3	29.4	29.5	27.9	26.8
Mean Minimum Temperature (°C)	14.9	18.9	20.6	22.8	22.7	21.6	21.2	20.6	20.5	20.3	19.3	15.7
Total Rainfall (mm)	0.0	0.0	0.0	46.9	58.5	146.7	38.6	130.5	58.0	112.9	220.2	0.0
Highest Maximum Temperature (°C)	30.7	34.0	37.9	38.5	37.9	34.0	31.5	31.0	32.5	31.1	30.6	28.3
Lowest Minimum Temperature (°C)	11.0	16.6	17.0	19.6	20.0	18.3	20.4	19.7	18.8	15.6	17.0	13.8
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	0.0	44.5	15.7	44.5	20.2	34.0	8.8	46.2	157.5	0.0
1993												
Mean Maximum Temperature (°C)	29.8	31.2	34.1	36.4	35.9	31.0	28.6	27.4	28.5	29.2	28.1	26.7
Mean Minimum Temperature (°C)	15.6	18.1	21.3	23.2	23.0	21.8	21.2	20.7	20.3	20.9	19.3	16.8
Total Rainfall (mm)	0.0	0.0	2.7	1.2	21.3	60.2	97.4	80.3	64.3	207.4	48.9	100.7
Highest Maximum Temperature (°C)	31.4	34.0	36.8	38.5	39.6	35.0	32.2	30.0	31.6	31.8	30.8	28.5
Lowest Minimum Temperature (°C)	12.4	14.4	17.9	19.6	18.8	18.9	20.0	19.8	19.6	18.6	14.8	13.0
Heaviest Rainfall in 24 hrs (mm)	0.0	0.0	2.7	1.1	12.7	13.8	34.7	11.8	17.2	76.9	23.7	72.8

js/-

Senthil 28.2.94

METEOROLOGICAL DATA ON CHITRADURGA YEAR 1992. DURING APRIL, OCTOBER & DECEMBER (ON 10TH OF EVERY MONTH)

FREQUENCY OF OBSERVATION: EVERY 3 HOURLY. SOURCE: IMD-BANGALORE (INDIA).

ME		APRIL				OCTOBER				DECEMBER			
		TEMPERATURE	RELATIVE HUMIDITY	WIND SPEED IN KMPH	RAINFALL	TEMPERATURE	RELATIVE HUMIDITY	WIND SPEED IN KMPH	RAINFALL	TEMPERATURE	RELATIVE HUMIDITY	WIND SPEED IN KMPH	RAINFALL
5:30		25·20	065	006	NO RAINS	22·20	093	012	NO RAINS	16·40	086	004	NO RAINS
8:30		29·60	038	006	NO RAINS	25·40	087	012	NO RAINS	18·40	079	010	NO RAINS
11:30		34·00	033	014	NO RAINS	28·00	065	010	NO RAINS	22·40	058	010	NO RAINS
14:30		37·40	021	012	NO RAINS	28·00	060	012	NO RAINS	24·60	047	014	NO RAINS
17:30		36·20	020	010	NO RAINS	27·00	066	012	NO RAINS	24·20	043	012	NO RAINS
20:30		31·40	039	003	NO RAINS	24·20	078	008	NO RAINS	20·00	062	010	NO RAINS
23:30		27·00	069	010	NO RAINS	23·20	082	016	NO RAINS	19·00	073	008	NO RAINS
02:30		25·40	072	006	NO RAINS	22·60	090	014	NO RAINS	17·20	075	006	NO RAINS

KFR.

APPENDIX F: Financing pattern for HUDCO Schemes[34]

Category	Cost Ceiling (Rs.)	Max. Loan ceiling Rs.)	Extent of finance (%age)	Net interest rate (%age)	Repayment period (Years)
I EWS-Monthly Income upto Rs. 1250					
Rural					
Landless*	15,200	11,500	90	09	15
Landed	26,400	19,500	90	09	15
Village abadi including Repairs	4,800	**	100	09	11
Urban					
EWS House	26,400	19,500	90	09	15
Community Toilets	NA	NA	50	10	12
Repairs/ Additions	13,200	9,500	90	09	10
II LIG - Monthly Income over Rs. 1250 and upto Rs. 2650					
Rural-Urban					
LIG House	80,000	55,000	85	13 12	15 10
Repairs/ Add.	30,000	21.00	85	12	10
III MIG-Monthly Income over Rs. 2650 and upto Rs. 4450					
Rural-Urban					
MIG House	----	1,75,000	75	15.00	10
Repairs/ Additions	--	55,000	50	15.00	10
IV HIG-Monthly Income over Rs. 4450/-					
HIG House	----	3,00,000	60	16.00	15
Repairs/ Additions	----	1,00,000	60	16.00	10

34. The exchange rate for the US Dollar to the Indian Rupee in 1994 was US$1.00 = Rs.30.00 (approx.). This will translate to, for the income groups, as follows: i) for **EWS**, a monthly income less than US$40.00 ii) for **LIG**, a monthly income between US$40.00 - 90.00 iii) for **MIG**, a monthly income between US$90.00 - 150.00 and iv) for **HIG**, a monthly income of over US$150.00.